Journal

of

THE ROYAL AERONAUTICAL SOCIETY

FEBRUARY 1959

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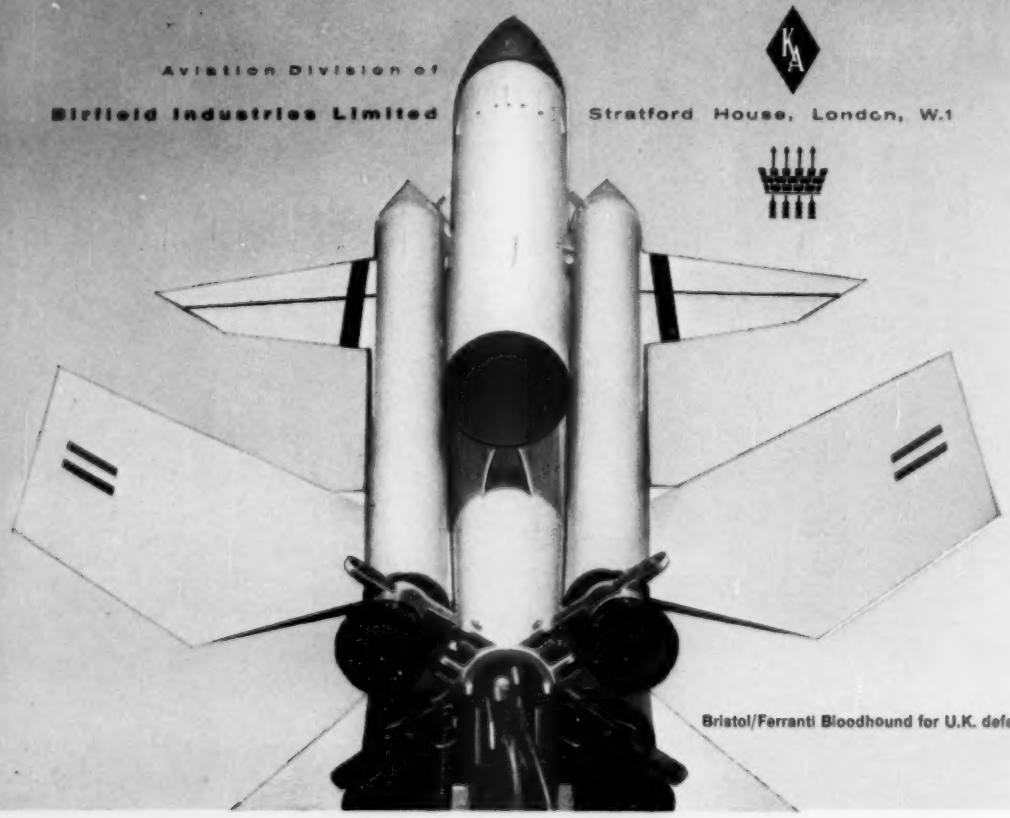

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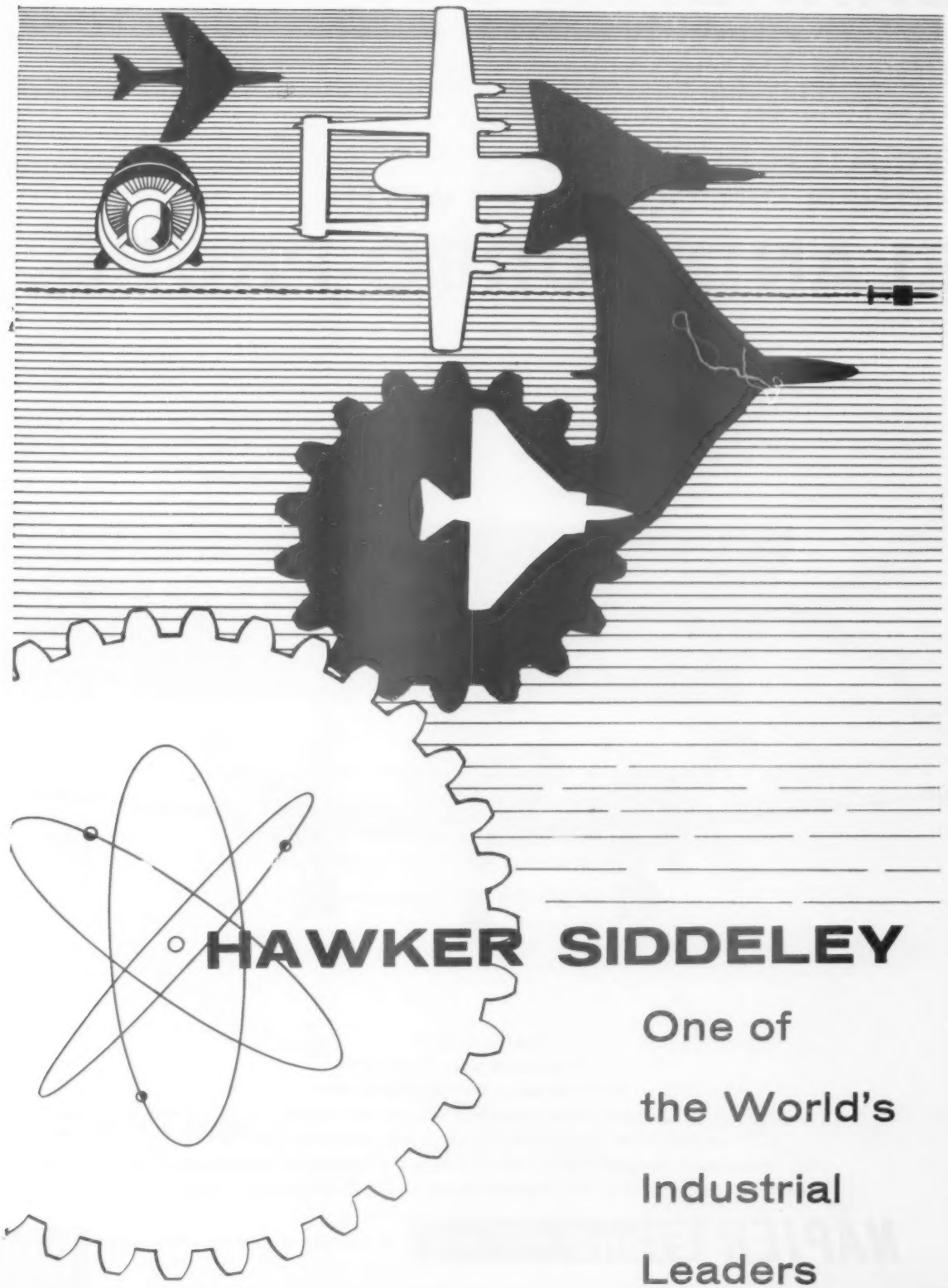
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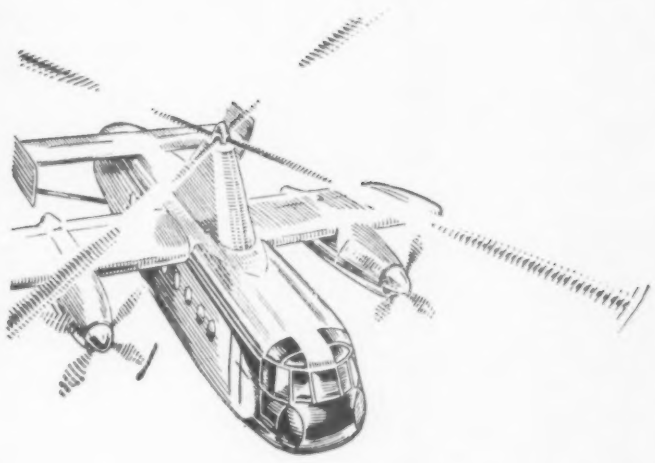

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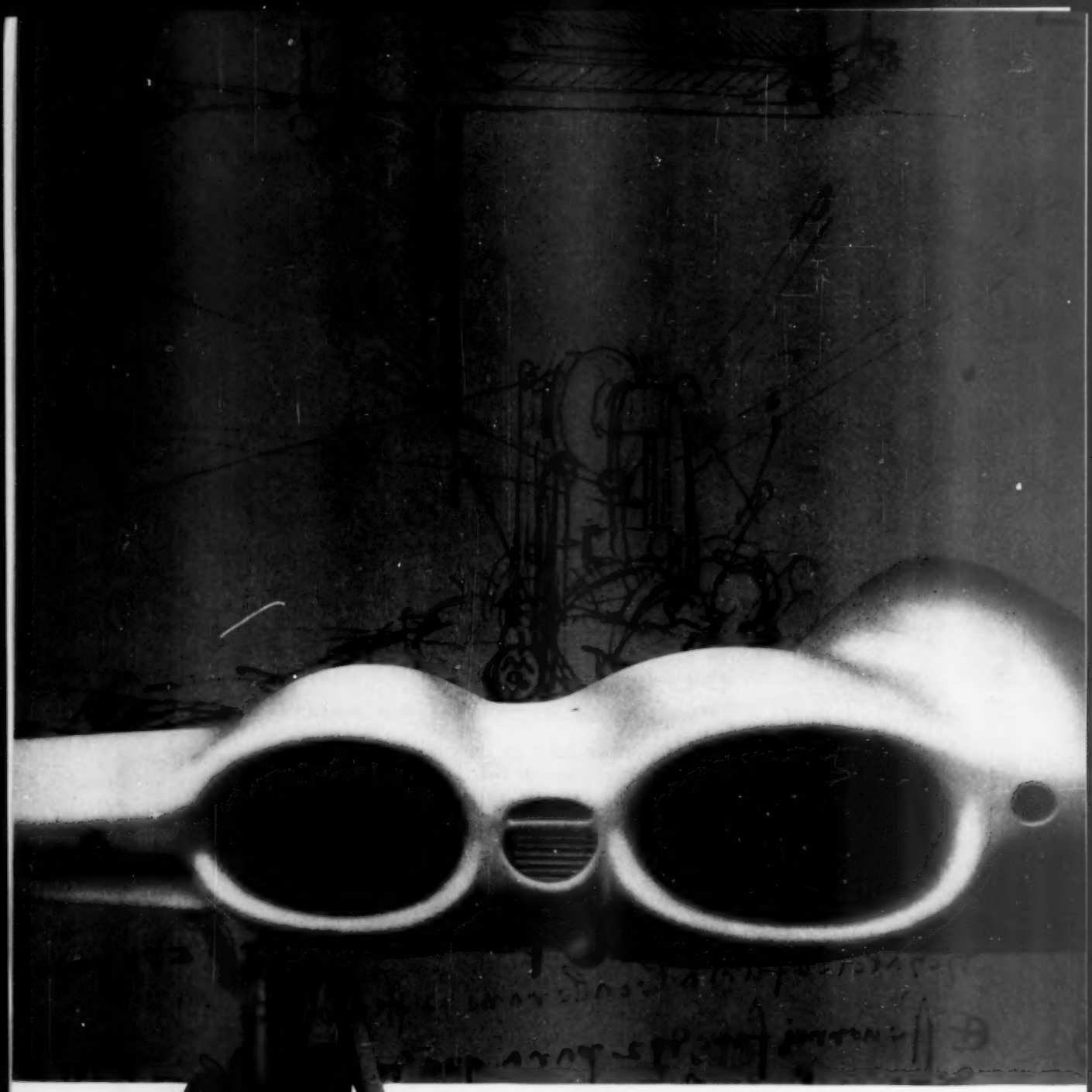

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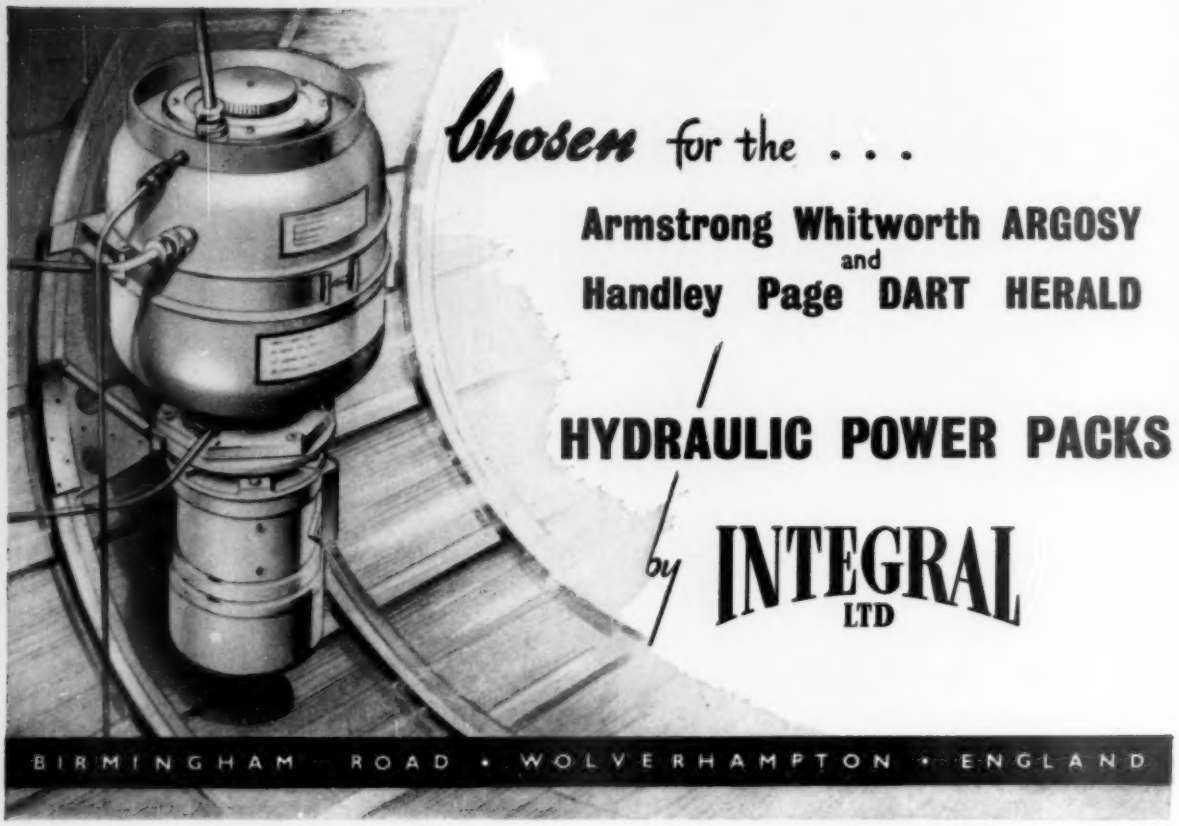

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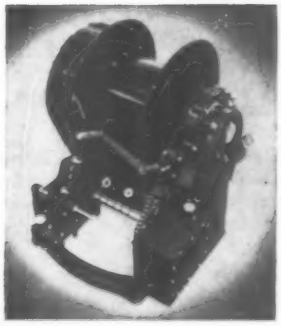

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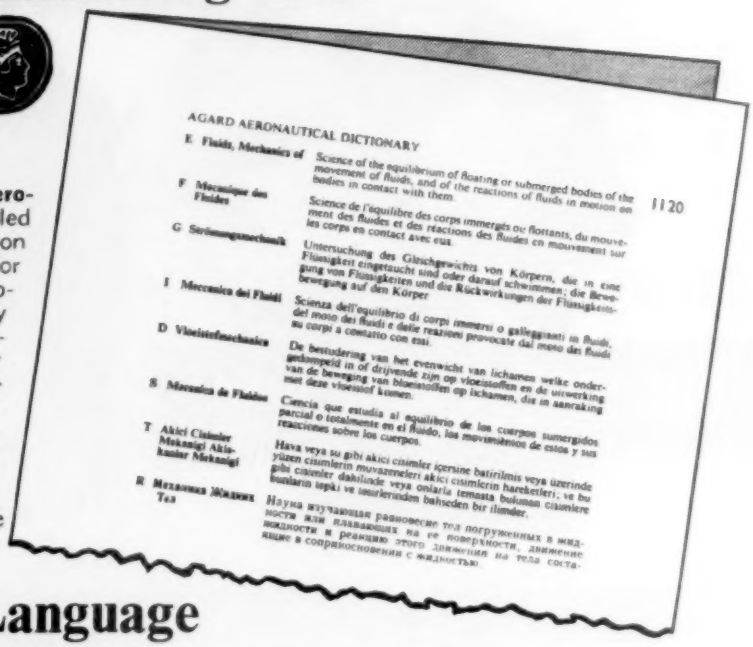
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Hon. Secretary: A. D. HOWARTH, A.R.Ae.S., Blackburn & General Aircraft Ltd., Brough.

CAMBRIDGE
President: Professor W. A. MAIR, F.R.Ae.S.
Chairman: C. F. C. SNEESBY, A.F.R.Ae.S.
Hon. Secretary: J. LUDFORD, A.R.Ae.S., Marshalls Flying School, Newmarket Road, Cambridge.

CHESTER
President: J. C. CORBY, O.B.E.
Chairman: R. G. HOARE, A.F.R.Ae.S.
Hon. Secretary: H. STRAWSON, Thornton Research Centre, P.O. Box 1, Chester.

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President: W. A. TAMBLIN, F.R.Ae.S.
Chairman: F. J. HAMILTON, A.F.R.Ae.S.
Hon. Secretary: H. E. VINCENT, A.F.R.Ae.S., de Havilland Aircraft Co. Ltd., Airspeed Div., Christchurch Aerodrome, Hants.

COVENTRY
President: H. M. WOODHAMS, C.B.E., F.R.Ae.S.
Chairman: W. J. PETERS.
Hon. Secretary: C. T. SCULTHORPE, A.F.R.Ae.S., Sir W. G. Armstrong Whitworth Aircraft Ltd., Whitley, Coventry.

DERBY
President: J. D. PEARSON, F.R.Ae.S.
Chairman: A. A. RUBBRA, F.R.Ae.S.
Hon. Secretary: W. R. BENDALL, A.F.R.Ae.S., Rolls-Royce Ltd.

GLASGOW
President: Professor W. J. DUNCAN, C.B.E., F.R.Ae.S.
Chairman: Dr. A. W. BABISTER, A.F.R.Ae.S.
Hon. Secretary: W. N. ALCOCK, Civil Engineer in Chief Department, Admiralty, Dalnottar House, Old Kilpatrick, Glasgow.

GLOUCESTER AND CHELTENHAM
President: R. H. BOUND, F.R.Ae.S.
Chairman: J. F. CUSS, A.F.R.Ae.S.
Hon. Secretary: J. G. RUSSELL, A.F.R.Ae.S., Rotol Ltd., Gloucester.

HALTON
President: Air Vice-Marshal H. D. SPRECKLEY, C.B., O.B.E., F.R.Ae.S.
Chairman: Air Commodore T. N. COSLETT, O.B.E.
Hon. Secretary: Flt. Lt. J. BEATTIE, A.R.Ae.S., Instrument Fitter Flight, Technical Wing, R.A.F. Halton.

HATFIELD
President: Sir GEOFFREY DE HAVILLAND, C.B.E., A.F.C., Hon. F.R.Ae.S.
Chairman: R. C. GRINTER, A.F.R.Ae.S.
Hon. Secretary: J. A. KIRK, A.F.R.Ae.S., de Havilland Propellers Ltd., Hatfield, Herts.

HENLOW
President: Air Marshal Sir ARTHUR MCDONALD, K.C.B., A.F.C.
Chairman: Wg. Cdr. I. D. H. GIBBINS, M.B.E., A.F.R.Ae.S.
Hon. Secretary: Flt. Lt. A. H. CRAVEN, A.F.R.Ae.S., Officers' Mess, R.A.F. Technical College, Henlow, Beds.

ISLE OF WIGHT
President: Sir ARTHUR GOUGE, Hon. F.R.Ae.S.
Chairman: W. BROWNING, F.R.Ae.S.
Hon. Secretary: L. W. ROSENTHAL, A.F.R.Ae.S., Saro Structures Ltd., Folly Works, Whippingham, E. Cowes, Isle of Wight.

LEICESTER
Chairman: K. B. AYERS, A.F.R.Ae.S.
Hon. Secretary: A. C. THOMAS, A.R.Ae.S., c/o Auster Aircraft Ltd., Rearsby, Leics.

LONDON AIRPORT
President: G. W. HALL, F.R.Ae.S.
Chairman: R. L. LICKLEY, F.R.Ae.S.
Hon. Secretary: N. BROWN, A.R.Ae.S., B.O.A.C. H.Q., London Airport, Middlesex.

LUTON
President: A. T. SLATOR.
Chairman: H. E. CURTIS, A.F.R.Ae.S.
Hon. Secretary: L. A. WILLOTT, A.F.R.Ae.S., Hunting Aircraft Ltd., Luton Airport.

MANCHESTER
President: Sir ROY H. DOBSON, C.B.E., J.P., Hon.F.R.Ae.S.
Chairman: C. E. FIELDING, O.B.E., F.R.Ae.S.
Hon. Secretary: J. A. E. WATERFALL, 56 Manor Avenue, Ashton-on-Mersey, Cheshire.

MERTHYR TYDFIL
President: CHARLES MCGIBBON.
Chairman: J. INGRAM.
Hon. Secretary: Dr. G. O. Forester, Chief of Research, Teddington Aircraft Controls Ltd., Cefn Coed, nr. Merthyr Tydfil, South Wales

PRESTON
President: Sir GEORGE H. NELSON.
Chairman: E. LOVELESS, A.F.R.Ae.S.
Hon. Secretary: J. H. GROUT, A.F.R.Ae.S., Aircraft Division, English Electric Co. Ltd., Warton Aerodrome, nr. Preston.

READING
President: Sir FREDERICK HANDLEY PAGE, C.B.E., Hon.F.R.Ae.S.
Chairman: R. J. FENNER, A.F.R.Ae.S.
Hon. Secretary: E. L. PEARSON, A.R.Ae.S., Handley Page (Reading) Ltd., The Aerodrome, Woodley, Reading.

SOUTHAMPTON
Chairman: D. B. SMITH, O.B.E., A.F.R.Ae.S.
Hon. Secretary: F. C. Kirkpatrick, A.R.Ae.S., Folland Aircraft Ltd., Hamble, Southampton.

SOUTHEND
Chairman: S. J. SMYTH, A.F.R.Ae.S.
Hon. Secretary: K. A. COLE, A.R.Ae.S., c/o Aviation Traders (Eng.) Ltd., Southend Airport, Essex.

SWINDON
Chairman: W. GILLESPIE, A.F.R.Ae.S.
Hon. Secretary: D. RIGG, A.R.Ae.S., Vickers-Armstrongs (Aircraft) Ltd., Supermarine Works, South Marston, Swindon.

WEYBRIDGE
President: Sir GEORGE EDWARDS, C.B.E., F.R.Ae.S.
Chairman: H. H. GARDNER, F.R.Ae.S.
Hon. Secretary: E. G. BARBER, A.F.R.Ae.S., Vickers-Armstrongs (Aircraft) Ltd., Weybridge.

YEOVIL
President: E. C. WHEELDON.
Chairmen: D. L. HOLLIS-WILLIAMS, F.R.Ae.S. and Dr. E. W. STILL, F.R.Ae.S.
Hon. Secretary: L. A. LANSDOWN, A.F.R.Ae.S., Westland Aircraft Ltd., Yeovil.

February 1959

NOTICES

Nomination of Candidates for Council

The following is an extract from the By-Laws:—

"The Twenty-one ordinary members (of the Council) shall be nominated and elected from among the members of the Society. At the date of their election at least ten shall be Fellows, and one at least shall be in each of the following classes: Associate Fellow, Associate and Graduate.

"Of the ordinary members of the Council that number necessary to create seven vacancies shall retire annually. The retiring members shall be those with the longest service since their election but they shall be eligible for re-election.

"Nominations of candidates for election to the Council must be received by the Secretary not later than 10th April in each year and shall include statements in writing by the candidates that they are willing to serve. The nomination forms shall be signed by one proposer and two seconders, all of whom shall be Voters."

Nomination forms may be obtained from the Secretary.

Astronautics and Guided Flight Section

The name of the Guided Flight Section has been changed to the Astronautics and Guided Flight Section. The Section is holding an informal Discussion evening on "Rocket Propulsion—Liquid and Solid" at 4 Hamilton Place on Tuesday 3rd March 1959 at 7 p.m. which is *for members of the Section only* and Graduates by invitation. *Admission will be by ticket only*, available on application to the Secretary.

New Year's Honours List

K.B.E.	Dr. G. W. H. Gardner (*Fellow*)
C.B.	Air Vice-Marshal G. Silyn Roberts (*Fellow*)
C.M.G.	S. F. Follett (*Fellow*)
C.B.E.	S. E. Clotworthy (*Fellow*)
	Group Captain J. C. Pope (*Associate Fellow*)
	R. H. Schlotel (*Fellow*)
O.B.E.	Thomas Bancroft (*Associate Fellow*)
	D. J. Farrar (*Fellow*)
	Major P. L. Teed (*Fellow*)
	Acting Group Captain A. S. Knowles (*Associate Fellow*)

The Twelfth Louis Blériot Lecture

The Twelfth Louis Blériot Lecture will be held at the Institution of Mechanical Engineers, Birdcage Walk, S.W.1., on Thursday 12th March 1959 at 6.0 p.m. (Tea at 5.30 p.m.). The Lecture will be on "The Griffon and the Prospect of Combining the Turbo-Ram-Jet Engine for Propulsion of Aeroplanes at High Speeds" by Monsieur l'Ingénieur Général de l'Air Noël Daum.

The Institute of Physics, Delft Conference, 1959

The Stress Analysis Group of the Institute of Physics, in collaboration with the Instituut T.N.O., will hold a conference at the Technische Hogeschool, Delft, from 31st March to 4th April 1959.

About 55 papers will be discussed and preprints should be available a month before the conference. The conference fee is one guinea for non-members of the Institute.

Details can be obtained from L. Lawrence, The Institute of Physics, 47 Belgrave Square, London, S.W.1.

Gliding Holidays

The British Gliding Association offers gliding holidays at many beauty spots in England and Scotland. Depending on location and time of year the cost varies from 12 to 20 guineas a week, which covers board and lodging, flying fees and instruction.

Further information can be obtained from the British Gliding Association, Londonderry House, 19 Park Lane, London W.1.

Presidential Reception—13th February 1959

A Presidential Reception will be held in the offices of the Society on Friday February 13th from 7.30 to 10.00 p.m. Members have been sent particulars and it is hoped as many as possible will be able to be present on this occasion. Tickets may be obtained on application to the Secretary, price one guinea each, which includes Buffet Supper.

Members wishing to attend who have not yet applied for tickets should do so immediately.

Mr. Gustavus Green, Honorary Companion

Honorary Companionship of the Society has been conferred on Mr. Gustavus Green for his work on the design and development of the early Green engines. The scroll of Honorary Companionship was presented to Mr. Green by the President, Sir Arnold Hall, before the Council meeting on 15th January 1959.

Mr. Green, who was born a year before the Aeronautical Society was founded, designed and built the first successful British aero engines, including 35 h.p., 60 h.p., 100 h.p., 150 h.p. and 300 h.p. models. The £1,000 Prize for the first circular mile flight was won by J. T. C. Moore-Brabazon (now Lord Brabazon) flying a Short No. 2 Biplane with a 35 h.p. Green engine in 1909; Colonel Cody used both the 60 h.p. and 100 h.p. engines in his biplanes from 1910-1913 and other pioneers who used Green engines included Mr. Robert Blackburn in 1909, Mr. A. V. Roe and Mr. Claude Grahame-White. Many early types of British aircraft used Green engines as did three of the British Airships—the "Dirigible IIA," "Beta" and "Gamma."

Although a few Green engines were used during the 1914-18 War, production was concentrated on engines for coastal motor boats for the Navy.

Mr. Green was always a particularly modest and unassuming man and since his retirement in the early 1920s has devoted himself quietly to his hobbies. The Council wish to thank Mr. H. F. Cowley, a Companion of the Society, and an enthusiastic aeronautical historian, for his assistance in arranging the presentation to Mr. Green.

At least nine Green aero-engines are still in existence. The Science Museum has four, the Edinburgh Museum one, there is one at Farnborough and Commodore Fred May has one. In addition, Mr. Green still has two, a 60 h.p. model built in 1910 and a 35 h.p. of 1908 which are being restored by Mr. Green's son, Mr. H. F. Cowley and Mr. Cook at one time of the Aster Engineering Co., which built the production Green engines, and by Mr. Cook's daughter, Mrs. Goodwin, who is an engineer.

Mr. Gustavus Green receiving the Scroll of Honorary Companionship of the Society from the President, Sir Arnold Hall.

DIARY

LONDON

12th February

MAIN LECTURE★—Earth Satellites. W. H. Stephens. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. **Note venue.** 6 p.m. (Tea at 5.30 p.m.)

13th February

PRESIDENTIAL RECEPTION. 4 Hamilton Place. 7.30 p.m. to 10 p.m. Buffet supper will be served. Tickets one guinea each obtainable from the Society. *See Special Notice.*

17th February

LECTURE—Engine Starting Systems. R. H. Woodall. Library, 4 Hamilton Place. 7 p.m.

19th February

LECTURE★—Theoretical Studies of Guided Missile Control Systems. E. G. C. Burt. Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

24th February

LECTURE—The Flight Development of an Aircraft Before and During its Operation. Dr. A. E. Russell, C. Abell, Dr. E. J. Warlow-Davies. Library, 4 Hamilton Place. 7 p.m.

5th March

FIRST FAIREY MEMORIAL LECTURE—AT LONDON AIRPORT BRANCH—Sir Richard Fairey—An Appreciation. G. W. Hall. Feltham Hotel (adjoining Feltham Station). 6.45 p.m.

10th March

LECTURE—Water and Ice in the Atmosphere. R. F. Jones. Library, 4 Hamilton Place. 7 p.m.

12th March

TWELFTH LOUIS BLERIOT LECTURE—The Griffon and the Prospect of Combining the Turbo-Ram-Jet Engine for Propulsion of Aeroplanes at High Speeds. Monsieur l'Ingénieur Général de l'Air Noël Daum. Institution of Mechanical Engineers, Birdcage Walk, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

19th March

LECTURE★—Long Range Missiles. E. C. Cornford. Institution of Civil Engineers, Great George Street, S.W.1. 6 p.m. (Tea at 5.30 p.m.)

★ Arranged by the Astronautics and Guided Flight Section.

GRADUATES' AND STUDENTS' SECTION

25th February

Deck Landing of Naval Jet Aircraft. Lt.-Cdr. D. J. Whitehead. Library, 4 Hamilton Place. 7.30 p.m. (Coffee at 7 p.m.)

4th March

Annual General Meeting and Film Show. Library, 4 Hamilton Place. 7.30 p.m. (Coffee at 7 p.m.)

25th March

Aircraft Escape Techniques. J. Martin. Library, 4 Hamilton Place. 7.30 p.m. (Coffee at 7 p.m.)

BRANCHES

16th February

Henlow—Student Members Papers. Building 62, R.A.F. Technical College. 7.30 p.m.

18th February

Coventry—The Armstrong Whitworth Argosy—Lecturettes by Members of the Design Staff. Wine Lodge, Corporation Street. 7.30 p.m.

Southampton—Rockets and Interplanetary Flight. W. N. Neat. Institute of Education, University of Southampton. 8 p.m.

Weybridge—Aircraft Carriers. J. C. Lawrence. Apprentice Training School, Vickers-Armstrongs (Aircraft). 6.10 p.m.

19th February

Bristol—Junior Committee Lecture—Cosmic Radiation. Prof. C. F. Powell. Filton House. 6 p.m.

25th February

Bristol—C.A.A./A.R.B. Lecture. Future Safety Requirements in Air Transport. Filton House. 6 p.m.

Christchurch—Navigation Aids. G. E. Beck. Kings Arms Hotel. 7.30 p.m.

Hatfield—Development of the P.1 Aircraft. F. W. Page. de Havilland Restaurant. 6.15 p.m.

Preston—Operational Problems in Supersonic Flight Testing. R. P. Beamont. R.A.F. Association Hall. 7.30 p.m.

26th February

Belfast—Noise and its Effects on Aircraft Structures. M. O. W. Wolfe. Lecture Hall LG8, David Keir Building, The Queen's University. 7 p.m.

Isle of Wight—Development of Submarines. R. N. Newton. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

Southend—Aircraft Electrical Installations. G. G. Wakefield. Labour Hall, Boston Avenue. 7.30 p.m.

2nd March

Derby—Methods of Propulsion in Space. Dr. L. R. Shepherd. Rolls-Royce Welfare Hall, Nightingale Rd., 6.15 p.m.

Henlow—Beating the Heat Barrier. J. Taylor. Building 62, R.A.F. Technical College. 7.30 p.m.

3rd March

Glasgow—Production of the English Electric P.1. G. H. Taylor. Room 24, Royal College of Science and Technology. 7.15 p.m.

Luton—Missile Reliability. E. H. Ingomells. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

4th March

Brough—Aircraft Carriers. J. C. Lawrence. Lecture Hall, Electricity Offices, Ferensway, Hull. 7.30 p.m.

5th March

Cheltenham—Experiences of an Airline Pilot. Capt. O. P. Jones. St. Mary's College, St. George's Place. 7.30 p.m.

London Airport—MAIN SOCIETY LECTURE—First Fairey Memorial Lecture—Sir Richard Fairey—An Appreciation. G. W. Hall. The Feltham Hotel (adjoining Feltham Station). 6.45 p.m. Followed by the Branch Annual Dinner.

9th March

Halton—The Trans-Antarctic Expedition. Sqd. Ldr. J. Lewis. Branch H.Q., R.A.F. Halton. 6.45 p.m.

10th March

Boscombe Down—Film Show. Lecture Hall, A. & A.E.E. 5.45 p.m.

Cambridge—Satellites. Mr. Wilson. No. 1 Lecture Theatre, Cambridge University Engineering Laboratories. 8.15 p.m.

11th March

Bristol—Barnwell Memorial Lecture—Bristol Prototypes. C. F. Uwins. Filton House. 6 p.m.

Chester—Bird Flight. J. L. Pritchard. Lecture Theatre, Grosvenor Museum. 7.30 p.m.

Hatfield—Metallic Material for Supersonic Aircraft. G. Meikle. de Havilland Restaurant. 6.15 p.m.

Manchester—Chadwick Memorial Lecture—Factors in Air Transport Economics. N. E. Rowe. Reynolds Hall, College of Technology. 7.30 p.m.

Reading—An Introduction to Nuclear Power. H. C. Stone. Palmer Hall, West Street. 7.30 p.m.

Southampton—Aviation Medicine. Sqn. Ldr. D. R. H. Urquhart. Institute of Education, University of Southampton. 8 p.m.

Swindon—Development of the Aeroplane. H. H. Gardner. The College, Victoria Road. 7 p.m.

Weybridge—The Air Registration Board. R. E. Hardingham. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

16th March

Derby—The British Aircraft Industry. E. C. Bowyer. Rolls-Royce Welfare Hall, Nightingale Road. 6.15 p.m.

Henlow—Film Show. Building 62, R.A.F. Technical College. 7.30 p.m.

18th March

Christchurch—Materials for Supersonic Aircraft. G. Meikle. Kings Arms Hotel. 7.30 p.m.

Coventry—Servicing of Civil Aircraft. I. J. Gregory. Wine Lodge, Corporation Street. 7.30 p.m.

19th March

Isle of Wight—The Trials and Tribulations of Airline Operation. Captain J. N. M. Weir. Clubhouse, Saunders-Roe Sports and Social Club, Church Path, E. Cowes. 6 p.m.

24th March

Luton—Annual General Meeting. Napier Senior Staff Canteen, Luton Airport. 6.15 p.m.

25th March

Bristol—Annual General Meeting and Film Show. Filton House. 6 p.m.

Glasgow—New Supersonic Wind Tunnel (Blackburn and General Aircraft). A. C. Smith. Room 24, Royal College of Science and Technology. 7.15 p.m.

Preston—The Application of the Area Rule to Aircraft Design. W. T. Lord. Queen's Hotel, Lytham. 7.30 p.m.

Reading—Annual General Meeting and Film Show. Canteen, Western Manufacturing Ltd. 6.15 p.m.

Southampton—Annual General Meeting. Institute of Education, University of Southampton. 8 p.m.

Weybridge—(Joint meeting with the Institution of Mechanical Engineers.) Guidance and Control of Missiles. L. H. Bedford. Apprentice Training School, Vickers-Armstrongs (Aircraft) Ltd. 6.10 p.m.

News of Members

JOHN P. ASHFORD (*Student*), formerly Technical Engineer with Bristol Aircraft Ltd., is now an Engineer in the Reactor Engineering Department, Atomic Power Projects, Whetstone.

ROY ATKIN (*Graduate*), formerly in the London Office of the Blackburn and General Aircraft Co., is now in the Aerodynamics Office at Brough.

Major Y. BARSELA (*Associate*) is now with the Purchasing Mission at the Embassy of Israel, London.

DEREK W. BROWN (*Graduate*) is now a Lecturer in the Department of Aeronautical and Mechanical Design, Hatfield Technical College.

HUGH ST. L. DANNATT (*Associate Fellow*), formerly with Canadair Ltd., Montreal, has joined Remington Rand Unival, Division of Sperry Rand Corporation, as a Senior Engineer on Computer Research and Development.

Flt. Lt. N. GARDNER (*Associate Fellow*) has been posted from Work Study Duties in Maintenance Command to the R.A.F. Technical College, Henlow, for a Mechanical Engineering Course.

J. GURNEY (*Graduate*), formerly Systems Engineer is now a Project Engineer (Air Conditioning) at de Havilland Propellers Ltd., Hatfield.

J. F. HARRISON (*Associate Fellow*) has left Rolls-Royce where he was in charge of mechanical development at their Flight Mechanical Development Establishment at Hucknall and is now with Ericsson Telephones Ltd., Beeston, as Deputy Head of the Electro-Mechanical Division of the Research Laboratories.

Air Commodore A. A. F. HICKMAN (*Associate Fellow*), formerly Senior Training Officer at No. 4 School of Technical Training is now Senior Technical Staff Officer, Middle East Air Force at Episkopi.

J. A. G. HOLMES (*Associate Fellow*), formerly with Bristol Aircraft Ltd., is now a Design Engineer with the U.K.A.E.A. (Industrial Group) at Risley.

Professor J. H. HORLOCK (*Associate Fellow*), formerly Demonstrator (Engineering) at Cambridge University, is now the Harrison Professor of Mechanical Engineering at The University of Liverpool.

Squadron Leader W. D. HUNTER (*Associate Fellow*) has left the Structures Department, R.A.E., Farnborough, and is now at the Royal Air Force Staff College, Bracknell.

J. A. KELLY (*Associate Fellow*), formerly with Hawker Aircraft Ltd., Dunsfold, is now Chief Inspector, Microcell Ltd., Camberley.

D. MACFARLANE (*Associate*) of the Ministry of Supply has been transferred from the Technical Costs Branch to Air Technical Publications, at Chessington.

A. S. M. MALHOMME DE LA ROCHE (*Graduate*) is now a Stress Engineer with the Fairey Aviation Co. Ltd., Hayes.

Wing Commander E. H. MAULE (*Associate Fellow*) has returned from the U.S.A. and taken up an appointment in D.A. Mech. at the Ministry of Supply.

Flight Lieut. W. F. MEUCHAN (*Associate Fellow*) has returned from a Missile Course in the U.S.A. and is now at the Royal Air Force Station at Feltwell, Norfolk.

JAMES C. OSBORNE (*Associate Fellow*) formerly of Thompson Products, Cleveland, is now Resident Engineer in the New England Area with the Parker Aircraft Co. of Los Angeles.

Lieut. K. G. PAUL, R.N. (*Associate Fellow*) has been appointed to the Royal Australian Navy for two and a half years and will be serving on H.M.A.S. *Albatross* at Nowra.

C. A. PENBERTHY (*Associate Fellow*), formerly Commercial Manager, Dowty Hydraulic Units Ltd., is now Director and General Manager of Alfred Miles Ltd., Cheltenham.

Squadron Leader R. H. PHILLIPS (*Associate*) has retired from the Royal Air Force and has taken an appointment with the Kellogg International Corporation.

J. ROSE (*Associate Fellow*) formerly Technical Assistant at Vickers-Armstrongs (Aircraft) Ltd., is now with Pirelli-General Cable Works Ltd., Eastleigh as a Designer.

C. B. A. SCHIFF (*Associate*), formerly Assistant to the Chief Inspector, has been appointed Deputy Chief Inspector for Manufacture at Bedek Aircraft.

R. R. SHAW (*Associate Fellow*), formerly Head of the Airworthiness Branch, Dept. of Civil Aviation, Australia, is now Technical Development Controller at Qantas Empire Airways Ltd.

Dr. W. A. J. WALL (*Associate Fellow*) formerly with Rotol Ltd., of Gloucester, is now with the Health and Safety Branch of the Industrial Group of the Atomic Energy Authority, Risley.

A. R. WOODWARD (*Associate Fellow*), formerly a Research Engineer, has been appointed Head of the Joining Division of the Development Department at Aluminium Laboratories Ltd., Banbury.

Elections

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Philip Peter Benham (*from Graduate*)
Alan Charlton Brown
Bryan Robert Alexander Burns (*from Graduate*)
Vithal Govind Gadgil
Peter John Harvey (*from Graduate*)
Charles Milford Jennings
Donald Joseph (*from Graduate*)
Derek Paul Morriss (*from Graduate*)
William Alan Pollard (*from Graduate*)
Janusz Stanislaw Przemieniecki (*from Graduate*)
John Andrew Robert Mason Reid
William Socha (*from Companion*)
Donald Francis Vowles (*from Graduate*)
Czeslaw Andrzej Zborowski (*from Graduate*)

Associates

David Drummond Anderson (*ex Associate*)
Anthony Birch
John Calvin Jones (*from Student*)
Henry Radnitz
Attur Krishna Iyer Subbiah
Leslie Frederick Wilton (*from Student*)

Graduates

Ross Dunstan Barkla
Norman William Beattie
Brian Lucas Bennett (*from Student*)
Jonathan Guy Chaplin
John David Davis
John Kirkhope Foden (*from Student*)
Roy Alan Green (*from Student*)
Peter John Mantle (*from Student*)
Basil John Taylor

Students

Rajni Bhagat
John Patrick Billingham
Ronald Henry Glynn
David Gregory
Robin Anthony Jowit
Henry McDonald
Baidya Nath Nag
Norman Anthony Llewellyn Noott
Keith Pugh O'Brien
Frederick Gerald Ross
Mahesh Chandra Sharma
Nicholas Valery
Michael John Walker

Income Tax Relief

Copy of a letter from Chief Inspector of Taxes Branch, Inland Revenue, Dated 17th October 1958.

Reference: C.I./SUB/306

Dear Sir,

I have to inform you that the Commissioners of Inland Revenue have approved The Royal Aeronautical Society for the purposes of Section 16, Finance Act, 1958, and that the whole of the annual subscription paid by a member who qualifies for relief under that Section will be allowable as a deduction from his emoluments assessable to income tax under Schedule E. If any material relevant change in the circumstances of the Society should occur in the future you are requested to notify this office.

I should be glad if you would inform your members as soon as possible of the approval of the Society. The circumstances and manner in which they may make claims to income tax relief are described in the following paragraphs, the substance of which you may care to pass on to your members.

Commencing with the year to 5th April 1959, a member who is an office holder or employee is entitled to a deduction from the amount of his emoluments assessable to income tax under Schedule E of the whole of his annual subscription to the Society *provided that*—

(*a*) the subscription is defrayed out of the emoluments of the office or employment, *and*,

(*b*) the activities of the Society so far as they are directed to all or any of the following objects—

(*i*) the advancement or spreading of knowledge (whether generally or among persons belonging to the same or similar professions or occupying the same or similar positions);

(*ii*) the maintenance or improvement of standards of conduct and competence among the members of any profession;

(*iii*) the indemnification or protection of members of any profession against claims in respect of liabilities incurred by them in the exercise of their profession;

are relevant to the office or employment, that is to say, the performance of the duties of the office or employment is directly affected by the knowledge concerned or involves the exercise of the profession concerned.

A member of the Society who is entitled to the relief should apply to his tax office as soon as possible *after* 31*st October* 1958, for form P358 on which to make a claim for adjustment of his pay as you earn coding.

Yours faithfully,

(*signed*) T. Dunsmore,

Senior Principal Inspector of Taxes.

The Secretary,
The Royal Aeronautical Society.

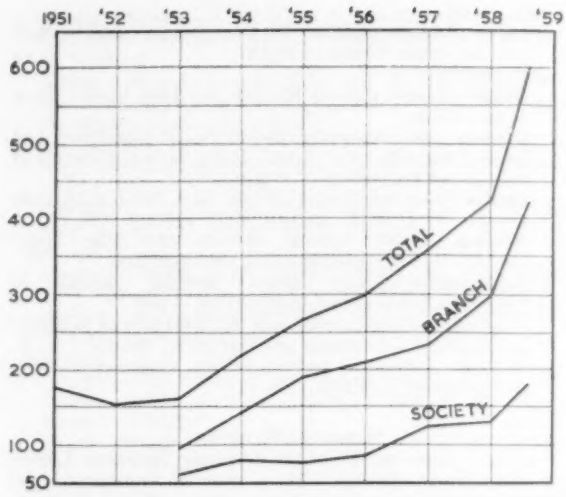
Brough Branch Tops 600 Membership Mark

Wednesday 10th December 1958 was a red letter day for Brough Branch. It reached a total paid up membership of 600 for the first time in its thirty years of existence.

This figure of 600 shows an increase of 300 since May 1956, and has coincided, generally speaking, with the increase of technical staff at Blackburn and General Aircraft Ltd. However, 170 of this increase has occurred during the past seven months and it is this jump in the figures which is particularly gratifying (*See* Figure).

We now have 184 Society Members, which raises our position from being the 8th largest branch at the beginning of this financial year to the 4th largest branch at the present time. Our immediate numerical superior is Coventry branch with about 240 Society Members, and they are our next target.

Our membership drive started because, at the beginning of 1958, we were concerned at the number of Society Members on our lists whom we suspected had not paid their subscriptions to Hamilton Place! Brough do not ask for an additional branch subscription from Society Members, so that we did not have any very reliable way of finding defaulters.



A Membership Sub-Committee was formed and they took rapid action. The list of members was replaced by a card system, *i.e.* a card for every member, red for Society Members and white for Branch Members. Cards were entered only upon proof of the subscription having been paid since 1st January 1958. This was easy for Branch Members, the subscription receipt counterfoils being proof of payment. But Society Members had to be written to individually, a form being enclosed for them to sign to the effect that they were members of the Society for the year beginning 1st January 1958.

While this was going on the "Grape Vine" was overhauled. The "Grape Vine" is a number of keenly interested members who are distributors of tickets and propaganda and collectors of subscriptions, etc. Their number was increased from twelve to twenty-five in key locations either within Blackburns or outside at places like Hull College of Technology. They are the direct contact with the members, and upon them depends the success or otherwise of almost everything we do. We keep them well informed of Society and Branch affairs, and they in turn tell us of the varied opinions of the members.

The first effect of our "no pay, no card" policy was a depressing reduction in membership. However, we did know that our figures were true and that, provided we continued with the same policy, our capitation grant from the Society would be genuinely deserved. From these sombre reflections, the membership drive grew. Many past members on our old membership list had not paid since 1st January, and consequently there was no card for them. Lists of their names were sent to the "Grape Vine," and subscriptions began to come in.

A number of other methods of finding prospective members were pursued. These were:—

(1) The 1955-56 Year Book list of Society Members and a special list, supplied from Hamilton Place, were searched for non-members of the Branch living in our area.

(2) Each "Grape Vine" member made a personal canvas in his or her local circle.

(3) A considerable number of prominent people, inside and outside Blackburns, who for years had been sent complimentary lecture tickets, were contacted.

(4) Most of those listed on the weekly return of new starters at Blackburns were also contacted.

All of these prospective members were either contacted personally or received individual letters. The methods used have met, and are still meeting, with a varied amount of success. The most successful, however, is undoubtedly the personal contact through the "Grape Vine" and their contribution has been outstanding.

A membership drive of this nature must obviously be based on sound organisation at Branch level. The essentials of this are (1) an active committee which is always seeking new means of expression (2) well known lecturers speaking on subjects which cater for all tastes and ages (3) a continuous summer and winter programme, and (4) the co-operation of the local Companies engaged in aeronautical engineering. Brough is fortunate at present to have all of these essentials.

A. D. Howarth, A.R.Ae.S., *Hon. Secretary.*

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The Mechanism and Application of Effusion Cooling*

by

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SUMMARY: Effusion cooling consists in forcing a gas under pressure through a porous material thereby absorbing heat from the material and forming a heat insulating layer on the exposed surface. The internal heat transfer between the porous material and coolant is considered and the heat transfer coefficient obtained from experiment. An approximate analysis for the heat insulating effect based on a heat balance method is derived in detail and applied to experiments with porous plugs set into the side of a duct carrying hot gases, and to porous cylinders swept by hot gases. It has been found that this analysis applies reasonably accurately to the results of these experiments and of most of the published data. The manufacture of porous materials is discussed briefly and a representative list of commercially available materials is included. The application of effusion and sweat cooling to the blading and combustion chamber linings for gas turbines, rocket motors and the outside skin of flying vehicles is considered.

1. Introduction

There are many instances in aeronautical engineering in which materials are subjected to high temperatures. The blading and casing of gas turbines, combustion chamber liners, rocket nozzles and the outside skin of the flying vehicle itself are but a few examples. There is an urgent demand for means whereby the maximum operating temperature can be increased. Most types of propulsion engine benefit in overall performance by an increase in the maximum operating temperature[1]. The higher speeds now envisaged for most kinds of flying machine bring them nearer to the so-called "thermal barrier." Cooling the surfaces exposed to these high temperatures can be done in many ways. An ideal method is to prevent the heat from actually reaching the surface. This can be done in part by coating the surface with a low thermal conductivity layer, and the lower the conductivity the better. Comparative values for some typical insulating materials are given in Table I. The solid materials could be bonded as a thin layer to the surface. The steam, air or hydrogen would have to be supplied continuously. It can be seen from Table I that air has the lowest thermal conductivity and is therefore a very good insulator. That the layer of air has to be renewed continuously is in fact an advantage in that the heat absorbed by it is returned automatically to the heat source. Heat is thus carried away from the stressed material which is always necessary, however low the thermal conductivity of the insulating layer, otherwise the hot gas temperature would be attained eventually.

Heat insulation or cooling by injecting a gas is called Effusion Cooling, and when a liquid is used it is generally referred to as Sweat Cooling. The coolant has to be distributed as a continuous layer on the exposed surface of the body to be cooled. This body has, therefore, to be porous throughout or be provided with a porous skin to which the coolant can be led through channels. Porous bodies can be made by powder metallurgy methods from stainless steel or other heat resisting materials. Practically any metal can be used which lends itself to breaking down into a fine powder. The powder, after grading, is compacted in a die to the required shape and then sintered at a temperature slightly below the melting point. Grain growth and bonding occur where the particles are sufficiently close together, but a network of fine channels or passages is left throughout the compact. Control of manufacturing conditions can give a variation in the size and distribution of these passages and this is expressed conveniently as the permeability to the flow of fluids. The rate of effusion of the coolant at the surface can thus be varied at different positions according to the local heat input. The provision of a porous skin or shell bonded to solid, load-carrying members overcomes the obvious difficulty with wholly porous

TABLE I
COMPARISON OF THERMAL CONDUCTIVITY VALUES

Material	*Thermal Conductivity at* 1000°C (10^{-4} c.g.s. units)
Alumina	120
Zirconia	45
Silica	20
Hydrogen	10·7
Asbestos	6
Steam	2·4
Air	1·9

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*Discussion is invited on this paper—ED.

bodies of their inherent mechanical weakness. This can be achieved by sintering a layer of metal powder to the solid member. An alternative is to make the shell out of woven metal gauze. Several layers of gauze can be sintered together to provide a rigid structure. Typical applications will be considered later.

It would appear that Oberth[2] in 1929 was the first to recognise the importance of sweat cooling for the cooling of rocket engines. The earliest experiments were carried out by Goddard[3] in 1930. A mixture of petrol and oxygen was burned in a 4-in. diameter rocket motor fitted with a porous ceramic liner and th at. The oxygen was used also as the coolant. The experiment seems to have lasted 11 seconds, but did demonstrate the feasibility of sweat cooling. Goddard's first patent including sweat cooling is dated 1938[4]. Similar early suggestions for rocket motors have been made by Meyer-Hartwig[5] in 1940 and Skoglund[6] in 1942. The application of the methods of effusion and sweat cooling to gas turbines was first suggested by Moore and Grootenhuis[7] in 1946. General reviews of these methods of cooling can be found in Refs. 8 and 9.

Only effusion cooling will be considered in this paper in an attempt to correlate the published experimental data with some new results in such a manner as to be of ready use to the designer. The flow of fluids through porous systems has recently been reviewed extensively by Eisenklan[10]. The specific cases of flow through porous metals made by powder metallurgy methods and through sintered gauze have been measured and correlated for design purposes by Grootenhuis[11, 12]. The flow problem is not considered here.

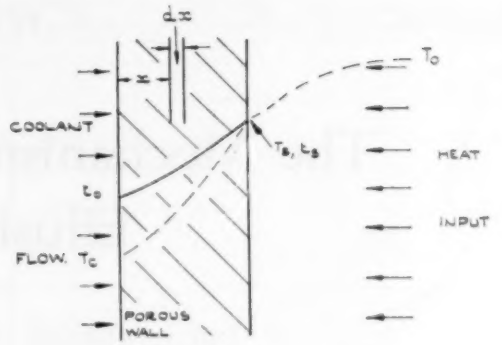
2. Mechanism of Effusion Cooling

The temperature distributions associated with the passage of a coolant through a porous wall exposed to heat on one side is illustrated in Fig. 1. The mechanism of cooling is two-fold: firstly, heat is abstracted from the wall by the coolant as it passes through it and secondly, a heat absorbing layer is formed on the outside. Any heat passing into the surface will have to flow through the layer of coolant effusing outwardly in the opposite direction. Only a fraction of this heat will reach the surface as some of it will be absorbed by the coolant, the amount depending upon the flow rate and the specific heat. Practically no heat will reach the surface with a large flow of coolant. The ideal for any cooling method will then have been achieved in that the entire wall temperature will be that of the coolant at inlet.

2.1. HEAT TRANSFER WITHIN POROUS MATERIALS

The temperature gradients in the porous wall and in the coolant stream are shown in Fig. 1. The direction of heat flow by conduction in the wall is opposite to the flow of coolant. Heat is transferred from the wall to the coolant and the enthalpy of the latter will rise. A heat balance for an element, dx, at distance x from the inlet side yields the equation: —

$$k_s \frac{d^2t}{dx^2} = h'(t-T) = G_c c_p \frac{dT}{dx} \quad . \quad . \quad (1)$$



——— TEMPERATURE DISTRIBUTION INSIDE POROUS WALL
– – – TEMPERATURE DISTRIBUTION IN COOLANT

FIGURE 1. Temperature distributions with effusion through a porous wall.

where

k_s thermal conductivity of the porous material based on the geometrical cross-sectional area
t wall temperature
T coolant temperature
h' heat transfer coefficient per unit *volume* of porous material
G_c mass flow per unit frontal area
c_p specific heat of the coolant

The wall temperature can be eliminated from this equation, giving for the coolant temperature the equation: —

$$\frac{d^3T}{dx^3} + \frac{h'}{G_c c_p}\frac{d^2T}{dx^2} - \frac{h'}{k_s}\frac{dT}{dx} = 0 \quad . \quad (2)$$

with the solution: —

$$T = \alpha + \beta e^{(B-A/2)x} + \gamma e^{-(B+A/2)x} \quad . \quad (3)$$

where

$$A = \frac{h'}{G_c c_p} \text{ and } B = \sqrt{\left\{\frac{h'}{k_s} + \left(\frac{A}{2}\right)^2\right\}}$$

and α, β and γ are constants of integration. The wall temperature can be obtained from the second part of equation (1): —

$$t = T + \frac{1}{A}\frac{dT}{dx}$$

or substituting equation (3): —

$$t = \alpha + (\tfrac{1}{2} + B/A)\,\beta e^{(B-A/2)x} + (\tfrac{1}{2} - B/A)\,\gamma e^{-(B+A/2)x} \quad . \quad . \quad (4)$$

These equations were first presented by Grootenhuis and Moore[13]. A similar approach was subsequently published by Weinbaum and Wheeler[14] but their analysis led to an error in sign in one of the equations, giving rise to erroneous conclusions. Berger[15] unfortunately copied this mistake in his attempt to allow for longitudinal heat flow. A complete solution of the problem in three dimensions has been presented by Bland[16].

The thermal conductivity of the porous material must be known. There are very few data for porous

metals. The results of measurements by Grootenhuis, Powell and Tye[17] for porous bronze and by Powell[18] for stainless steel are presented in Fig. 2. The bronze results gave a unique correlation, independent of particle size, along a straight line drawn from the point for solid bronze to intersect the abscissa at a porosity of 47·64 per cent, which is the maximum porosity that can be attained on packing equal sized spheres. Analogous measurements of the electrical conductivity for bronze and three other porous metals have supported this correlation. Two of the measurements for stainless steel are for porosities much greater than 47 per cent and would not be expected to conform with this correlation. The manufacture of porous materials with such large porosities is considered in Section 5.1.

The internal heat transfer coefficient, h', must be known for the solution of equations (3) and (4). There is again very little experimental work for porous metals. The coefficient has been determined by Grootenhuis, Mackworth and Saunders[19] for several grades of porous bronze passing air. The surface and air temperatures at the inlet and outlet sides were measured, thereby providing the four boundary conditions necessary for evaluating h' from equations (3) and (4). These measurements were then compared with a correlation of the heat transfer to beds of loose granules of very different materials. The basis of this correlation is a non-dimensional Nusselt number $Nu' = h'd^2/6(1-f)k$, where d is a measure of the particle size, f the porosity, and k the thermal conductivity of the gas passing through the bed. The factor $6(1-f)/d$ represents the surface area per unit volume for a bed of spheres and allows for the use of a heat transfer coefficient per unit volume (h'). The mass flow in the Reynolds number has been

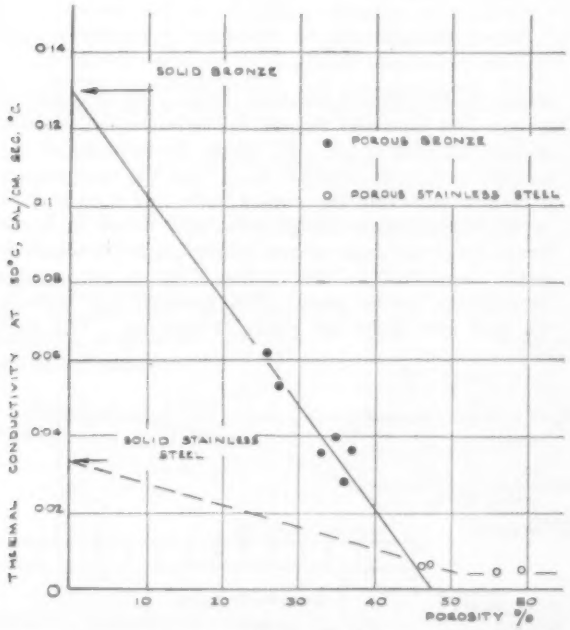


FIGURE 2. Thermal conductivity—porosity data for bronze and stainless steel.

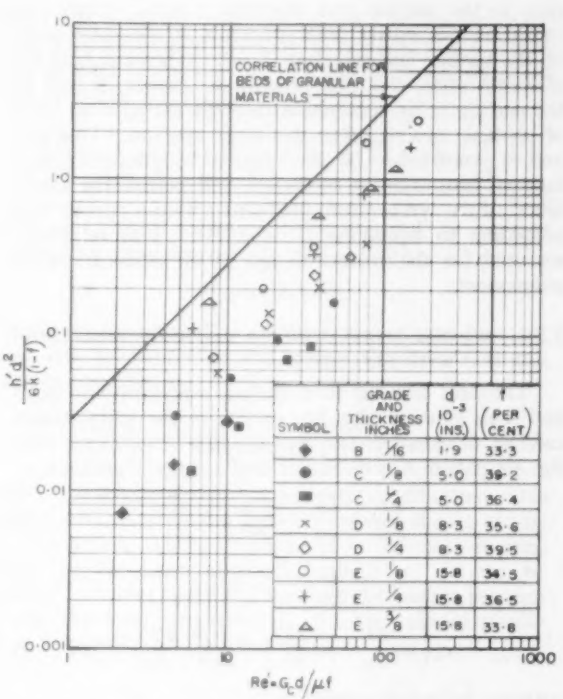


FIGURE 3. Internal heat transfer correlation for porous bronze.

divided by the porosity to represent the actual velocity in the pores. The result of this correlation, as shown in Fig. 3, is a straight line when plotted to a logarithmic scale. This line represents the mean of measurements for ten different materials by five sets of investigators. (For details of this correlation, not shown in Fig. 3, *see* Ref. 19.) The actual results for the porous bronze are shown in Fig. 3. The correlation is not altogether satisfactory, but this cannot be accounted for simply by variations in porosity which were between the rather narrow range of 33 and 40 per cent. The probable explanation lies in the deformation of the spherical particles during manufacture, which causes a loss of effective internal surface area, most especially for the smaller particles, which may explain their lower heat transfer values. The average particle size for each grade of bronze is given in Fig. 3. A mean line through each set of points is parallel to the main correlation line. This correlation is sufficiently general, however, to enable an estimate of the heat transfer coefficient for porous metals to be made as a first approximation. It should be realised that the heat transfer rate to a coolant flowing through a porous metal is very high indeed, due to the large internal surface area.

An interesting condition for the mechanism depicted in Fig. 1 is that the coolant must attain at outlet the surface temperature, assuming there is no heat input by radiation. The heat transfer within the porous wall is from the material to the coolant and therefore $t > T$ and at the surface $t_s \geq T_s$. Outside this surface, however, the coolant is the hotter and is transferring

heat to the surface and therefore $t_s \leqslant T_s$. Only one condition can satisfy both processes at the same point on the surface and therefore $T_s = t_s$. This will hold for all cases where the final process of transfer of heat to the surface is by conduction through the effusing layer of coolant, however thin this layer may be. This fact and a knowledge of the thermal conductivity and internal heat transfer coefficient will permit the calculation of the temperature gradients within a porous wall according to equations (3) and (4). This is clearly essential for the correct design of an effusion cooled component.

2.2. EXTERNAL HEAT TRANSFER TO POROUS SURFACES WITH EFFUSION

The heat transfer to a surface swept by hot gases and with effusion of a gas similar to the main stream can be determined for laminar flow conditions with the simplified Navier-Stokes and energy equations: —

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = \nu\frac{\partial^2 u}{\partial y^2} + U\frac{dU}{dx} \quad . \quad . \quad (5)$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad . \quad . \quad . \quad (6)$$

$$c_p\left(\rho u\frac{\partial T}{\partial x} + \rho v\frac{\partial T}{\partial y}\right) = \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) \quad . \quad (7)$$

with the boundary conditions: —

$$\left.\begin{array}{lll} \text{at} & y=0, & u=0, \quad v=v_0, \quad T=T_s \\ \text{at} & y=\infty, & u=U, \quad \dfrac{\partial u}{\partial y}=0, \quad T=T_0 \end{array}\right\} \quad . \quad (8)$$

where: —

x	direction along the surface
y	direction at right angles to the surface
u	velocity in the x direction
v	velocity in the y direction
v_0	velocity of effusion at the surface
U	free stream velocity
ν	kinematic viscosity
ρ	density
k	thermal conductivity
c_p	specific heat
T	temperature within the boundary layer
T_s	surface temperature
T_0	free stream temperature

Although these equations are similar to the well known cases of flow over solid surfaces, the boundary condition of a finite velocity at the surface in the y-direction (v_0) leads to considerable difficulties in their solution. Formal transformation and exact solution can be attained only if the velocity of effusion is made dependent upon the main stream conditions and the distance x, such that

$$\frac{v_0}{U} = -C\left(\frac{1+E}{2}\right)\left(\frac{\nu}{Ux}\right)^{\frac{1}{2}} \quad . \quad . \quad (9)$$

where C is an arbitrary constant,

$$E = -\frac{dP}{dx}\frac{x}{\rho U^2}, \text{ the Euler number,}$$

and P is the static pressure at x.

Much effort has been expended in obtaining exact solutions for different flow configurations, but all require this prescribed distribution of the velocity of effusion at the surface (*see*, for example, Refs. 20 to 25). This is difficult to achieve in practice and there does not appear to be any reliable experimental work to verify these theoretical solutions. The experiments by Mickley *et al*[26] would seem to have been abortive in this respect as the "coolant" was heated and blown through a heated porous surface into a cooler main stream. The heat flow was thus in the *same* direction as the mass flow which contradicts one of the basic features of the mechanism of effusion cooling. These theoretical solutions are, however, of great value to the designer as an indication of where to concentrate most effusion when there is a pressure gradient along the surface.

A constant and uniform velocity of effusion is more easily attained experimentally and will be considered in detail here. Only an approximate solution is then possible and an attempt may as well be made to alleviate the restricting conditions of laminar flow by making no assumptions as to the mechanism (laminar or turbulent) of transfer of heat to the surface.

3. Heat Balance Theory

A simple case to consider is a porous flat plate with uniform effusion starting at the leading edge. An element of such a plate is shown in Fig. 4, which also defines the symbols. The full line curve depicts diagrammatically the extent to which the boundary layer has developed, its shape is of no significance. It is assumed that there is no heat input by radiation.

For the rectangle *a*, *b*, *c*, *d*, of unit breadth, the heat balance in terms of temperature will be: —

$$U\bar{\rho}_0 T_0\delta + v_0'\rho_0' T_c x - T_0\left(U\bar{\rho}_0\delta + v_0'\rho_0' x - \int_0^\delta \rho u dy\right) - \int_0^\delta \rho u T dy = 0 \quad (10)$$

where the first term is the heat entering the rectangle at *ab* per unit time and the second term the net amount of heat entering at *ad*. By taking the velocity of the coolant as v_0', the density as ρ_0' and the temperature T_c at the entry into the porous plate, that is at surface *ef*, the second term includes the heat which is transferred from the main stream to the plate but which is again transferred to the cooling fluid on its passage through the porous plate. This assumes that there is no heat loss from the outer surface *ef*. The heat

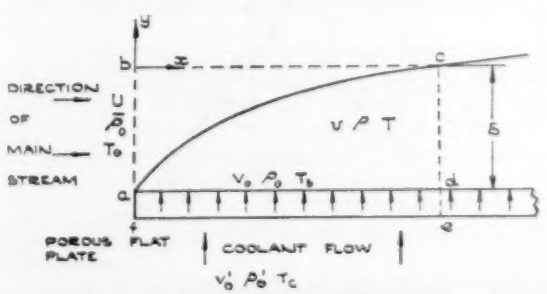


FIGURE 4. Element of a porous flat plate with effusion.

transfer coefficients between the coolant and the porous material are so large that this assumption will only be invalidated for very thin plates. The third term is the heat going out through the side *bc* and the fourth term that going out through *cd*. The kinetic temperatures have been neglected.

Several of the terms in the heat balance can be cancelled and the equation becomes: —

$$v_0'\rho_0' x\,(T_0 - T_c) = \int_0^{\delta} \rho u\,(T_0 - T)\,dy.$$

For a Prandtl number of the main stream equal to unity the velocity and temperature profiles are similar (*see* Eckert[27] for a justification of this for the case including injection through the surface). The equation can be rewritten thus: —

$$\frac{v_0'\rho_0'}{U\bar{\rho}_0} x \frac{T_0 - T_c}{T_0 - T_s} = \int_0^{\delta} \frac{\rho u}{\bar{\rho}_0 U} \frac{T_0 - T}{T_0 - T_s} dy \qquad (11)$$

where T_s is the surface temperature at x. The right-hand side is equal to the convection thickness and this in turn can be considered equal to the momentum loss thickness, in view of the assumed similarity of the velocity and temperature profiles; where by definition

$$v = \int_0^{\infty} \frac{u}{U^2}\,(U - u)\,dy. \qquad (12)$$

Whether the upper limit of integration is infinity or the thickness of the actual boundary layer, as required by equation (11), makes no difference provided the free stream velocity is constant. A velocity profile for a flat plate with uniform effusion is required to evaluate this expression. It need not be too exacting as the momentum loss thickness is not greatly affected by small errors in the assumed profile. A one-parameter law will be taken, after Schlichting[28], in the form: —

$$\frac{u}{U} = 1 - e^{-y/\delta_1} + K\frac{y}{\delta_1} e^{-y/\delta_1} \qquad (13)$$

where δ_1 is a measure of the boundary layer thickness and K is the form parameter.

A first integration of equations (5) and (6) with the boundary conditions as in equation (8) yields: —

$$\frac{\partial v}{\partial x} = \frac{v_0}{U} + \frac{\nu}{U^2}\left(\frac{\partial u}{\partial y}\right)_{y=0}$$

Substitution of the assumed velocity profile (equation (13)) and integration gives an expression for v, which can be used to replace the right-hand side of equation (11) such that

$$\frac{v_0'\rho_0'}{U\bar{\rho}_0} x \frac{T_0 - T_c}{T_0 - T_s} = -\tfrac{1}{2}\frac{\mu}{v_0\rho_0}\left(\frac{1+2K}{1+K}\right)\left(1 - K - \frac{K^2}{2}\right) \qquad (14)$$

The mass flow of coolant per unit area will be constant throughout the porous plate and therefore

$$v_0\rho_0 = v_0'\rho_0' = G_c.$$

Similarly the mass flow of the main stream per unit area can be written as $U\bar{\rho}_0 = G_0$. Equation (14) can then be rewritten as: —

$$\frac{T_0 - T_s}{T_0 - T_c} = -2\xi\frac{1+K}{(1+2K)(1-K-K^2/2)} \qquad (15)$$

where the left-hand side is a temperature efficiency ratio and $\xi = (G_c/G_0)^2\,Re$, a non-dimensional factor determining mainly the flow conditions in the main stream, with the Reynolds number $Re = G_0 x/\mu$. It can be shown[28, 29] that there is a unique relationship between ξ and the form parameter, K, for the velocity profile law of equation (13), given by: —

$$\xi = -1 - 2K - \frac{3}{4}\left(\frac{1+2K}{1+K}\right) + 2{\cdot}5\log_e\left(-\frac{1}{2K}\right) \qquad (16)$$

The temperature efficiency ratio is therefore dependent solely upon the factor ξ, which offers the basis of a unique correlation for experimental data obtained under widely varying conditions.

4. Comparison with Experiment

Two sets of experiments have been conducted[29]; the first with porous plugs fitted into a wall of a duct conveying hot gases and the second with porous cylinders inserted into a hot gas stream. The plugs were made either of porous bronze or of porous stainless steel. Details of the mounting are shown in Fig. 5. Its principle was to rely on an annular air gap for heat insulation between the plug and the duct walls, but on mechanical joints for alignment and sealing. The plug

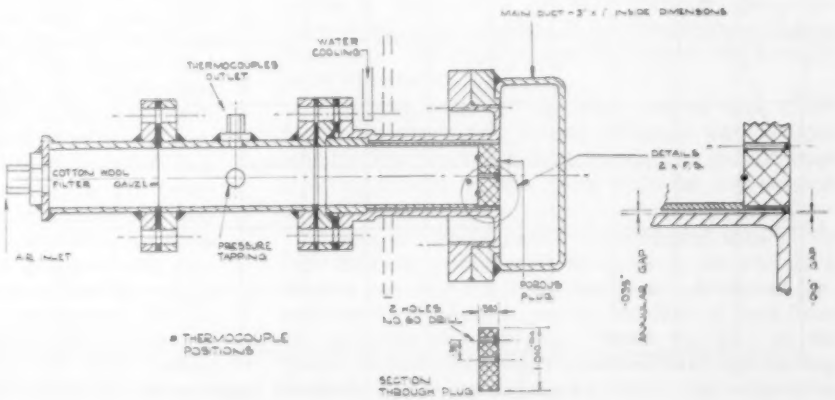


FIGURE 5. Mounting for porous plugs.

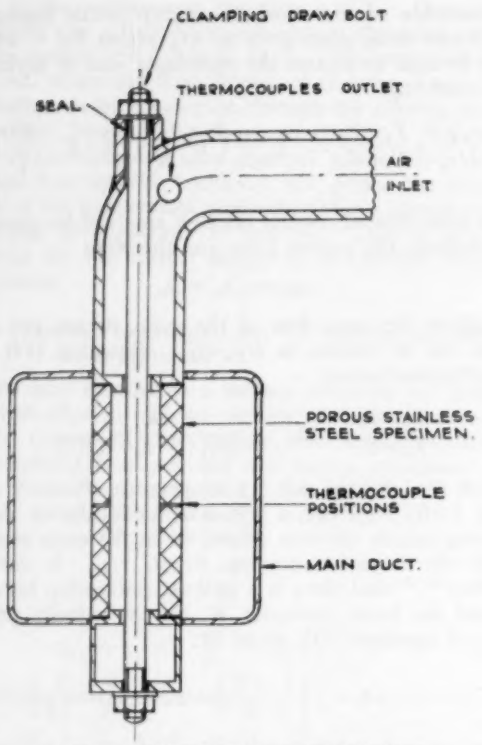


FIGURE 6. Mounting for porous cylinders.

was a push-fit into the recessed end of a thin tube of a low thermal conductivity material (Inconel) which was supported only at its other end by the water-cooled flange of the main part of the mounting. The plug and thermocouples were sealed in with a high temperature cement. The thermocouples were also welded to the porous material by a special spark technique. Preliminary experiments with a cooled, conductivity test bar in place of a plug showed that the heat transfer to the exposed surface on the inside of the duct conformed accurately to the general correlation for turbulent flow through a duct. Velocity and temperature traverses across the duct indicated uniformity. The hot gases were obtained from a gas-fired furnace and after dilution with secondary air were passed directly through the duct.

The maximum gas temperature was about 1,200°F. for a Reynolds number for the duct of 20,000. Higher Reynolds numbers could be obtained at lower temperatures. The plugs were cooled by forcing a metered flow of nitrogen through. Periodic checks of the cold flow characteristics guarded against leaks and clogging. Readings of the two thermocouples on the exposed surface were very nearly equal under all conditions, indicating a negligible cross-wise heat flow in the plug. Similarly the readings of the two thermocouples on the rear face were the same.

The cylinders were hollow and one was of porous bronze of diameter 0·9 in. and $1\frac{1}{8}$ in. long, and two were of porous stainless steel, of diameter $1\frac{1}{8}$ in. and $2\frac{7}{8}$ in. long. The maximum temperature in these experiments was 1,500°F. for a Reynolds number based on cylinder diameter of about 4,000*. The mounting of a stainless steel cylinder is shown in Fig. 6.

4.1. RESULTS OF EXPERIMENTS WITH PLUGS

The results for the two types of plug set into the wall of the duct have been correlated and compared with the heat balance theory (equation (15)) in Fig. 7.

*The experiments with the stainless steel cylinders were conducted at the Shell Petroleum Company Research Laboratory at Thornton; *see* Grootenhuis[10].

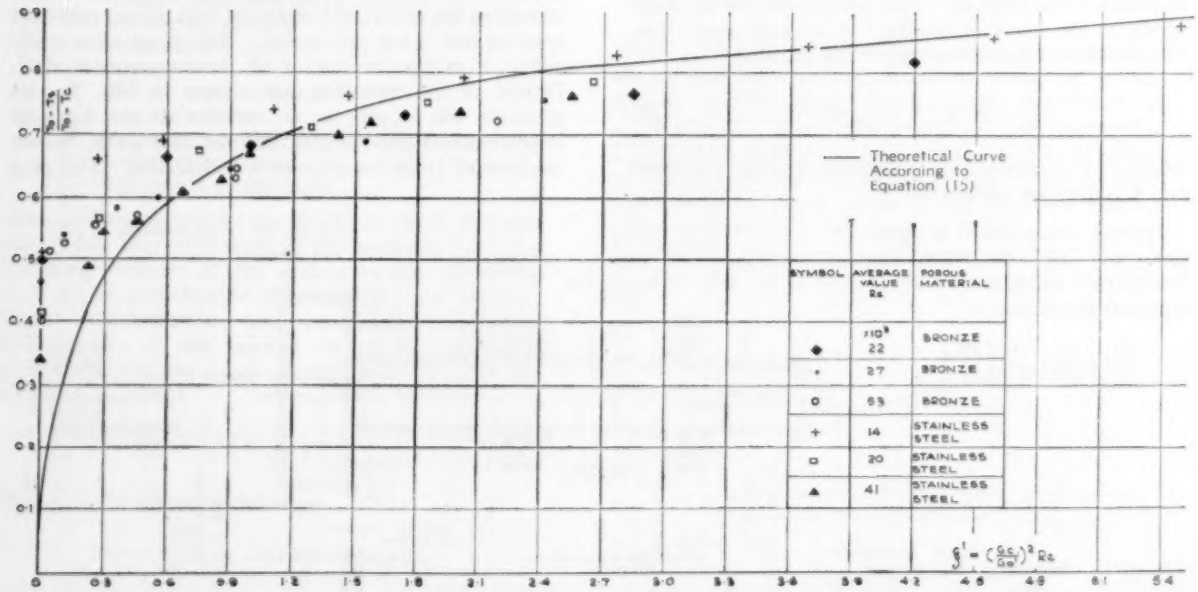


FIGURE 7. Correlation of effusion cooled porous plug results with theory.

The temperature efficiency ratio $(T_0-T_s)/(T_0-T_c)$, has been plotted to a basis of the factor $\xi=(G_c/G_0)^2\,Re$. The main stream mass flow and the Reynolds number have been based on the maximum velocity in the duct at the section where the plug was fitted. The linear dimension in the Reynolds number is the hydraulic mean diameter of the duct (equal to $1\frac{1}{2}$ in.). Agreement between different sets of results and with the theoretical curve is satisfactory, particularly if it be noticed that the scale of the graph is linear and not logarithmic, as is so often the case in heat transfer work. Disagreement is greatest at zero coolant flows. The surface temperature should theoretically equal the main stream temperature, but this cannot be, due to some heat loss from the mounting and plug to the surroundings when there is no coolant flow. There is no appreciable difference in the results for the bronze and stainless steel specimens. The only discernible trend is that results for the lowest potential heat transfer coefficient between the main stream and the plug lie closest to the theoretical curve.

4.2. RESULTS OF EXPERIMENTS WITH POROUS CYLINDERS

The results for the cylinders inserted into a stream of hot gases have been correlated and compared, again with equation (15), and are shown in Fig. 8. The surface temperature was the mean of readings of four thermocouples fitted at the mid-section, one in each quadrant. The main stream mass flow was the average flow per unit cross-sectional area of the duct. The Reynolds number has been based on the cylinder diameter. The bronze cylinder was cooled by methane and allowance for the difference in specific heat compared to air has been made. Agreement is again satisfactory, particularly between the results for the two types of cylinder.

4.3. CORRELATION OF PUBLISHED EXPERIMENTAL DATA

The first systematic experiments were carried out by Duwez and Wheeler[31] who passed the products of combustion from a petrol-air burner through a porous stainless steel cylinder, of one inch internal diameter and $1\frac{1}{2}$ in. long. Main stream gas temperatures up to 1,900°F. were used at Mach numbers approaching unity. Only one thermocouple was fitted in the wall, at the mid-section. No provision had been made to avoid heat flow into the specimen from the uncooled upstream section. This heat input by longitudinal conduction must have been excessive as the wall thickness and therefore the area of contact of the porous cylinder was large (thickness of cylinder about 0·85 in.). Nitrogen gas was used as the coolant. The heat transfer rate into the porous cylinder was calculated and was found to be a linear function of the main stream velocity, passing through the origin except for the data for $T_0=1{,}500$°F. (*See also* Richardson[32].) The results for each main stream temperature, except for 1,500°F., for the minimum and maximum Reynolds numbers only, have been correlated in Fig. 9. The cooling efficiency is less than would have been expected from

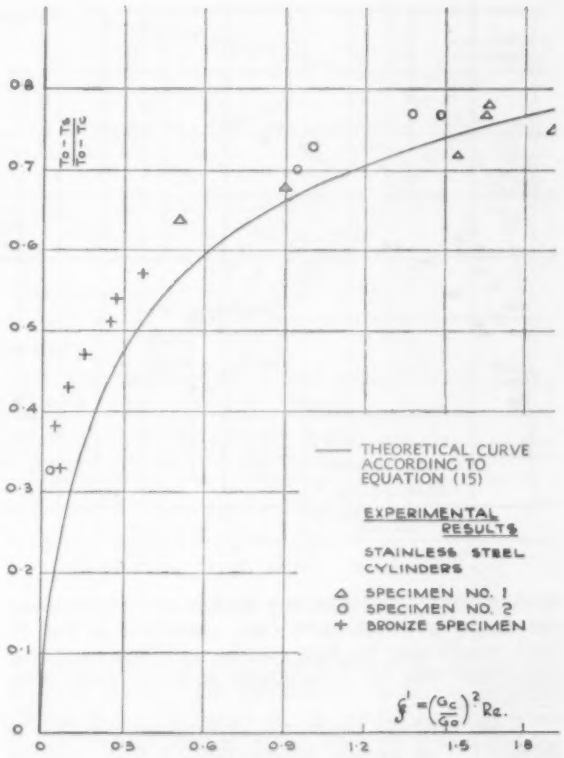


FIGURE 8. Results with porous cylinders.

the present theoretical analysis, presumably due to the heat flow into the specimen from the mounting.

Somewhat similar experiments using the same type of burner and a porous cylinder, 3 in. internal diameter, 6 in. long were carried out by Friedman[33]. Again only one thermocouple was relied upon to determine the surface temperature, situated at 5·6 in. from the start of the porous section. The description of the apparatus is very scanty and no mention is made of any heat insulation between the specimen and its mounting. Some representative sets of measurements, covering the entire range of Reynolds number, have been correlated in Fig. 9. Values of G_0 had to be obtained by re-calculation from the given values of Re, assuming appropriate viscosities. The coolant inlet temperature was assumed to be constant at 70°F.

The correlation of both these sets of data shows again that the highest cooling efficiency was obtained with the lowest potential heat transfer into the specimen (low Re values) as was found with the porous plug experiments.

Jakob and Fieldhouse[34] experimented with a one inch diameter porous plug mounted in the wall of a duct ($\frac{1}{2}$ in. × 2 in.) carrying hot gases. Adequate precautions were taken to prevent the flow of heat from the mounting into the plug. Water was used as the coolant in most of the experiments and very high cooling efficiencies were attained on account of the evaporative

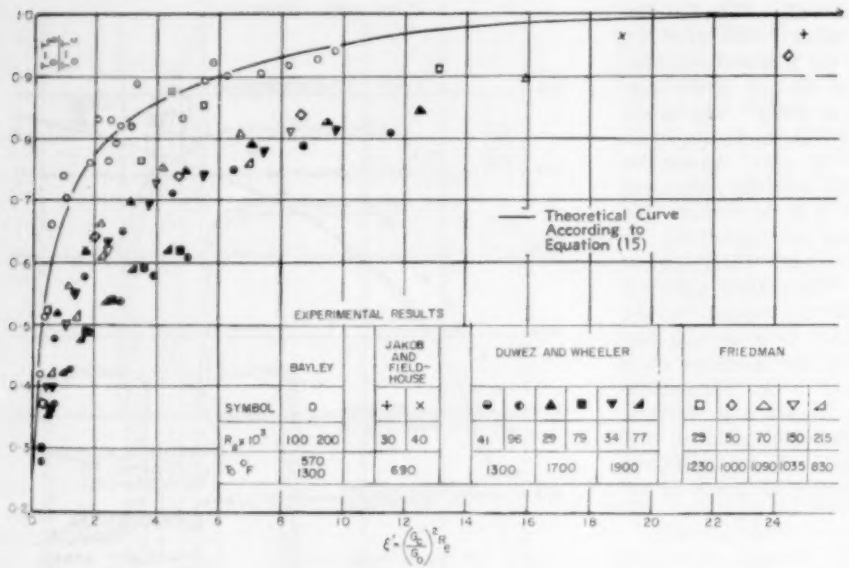


FIGURE 9. Correlation of published results.

cooling effect. Nitrogen was used in two experiments, the results of which have been correlated in Fig. 9. Both results were for high coolant mass flows and it is regrettable that no experiments at lower flows were carried out.

Some carefully conducted experiments are due to Bayley[35]. A porous bronze duct, 6·4 in. internal diameter and 21 in. long, made from $\frac{1}{8}$ in. thick sheet, was connected to the outlet of a kerosine-air burner. Several thermocouples were fitted along the duct so that longitudinal heat flow could be measured. Some heat did flow into the duct from the upstream mounting, but this was dissipated in the first quarter length. The temperature of the remaining length was fairly constant. Air was used as the coolant. These results have again been correlated in Fig. 9. The agreement with the theoretical curve is satisfactory.

A similar experiment was carried out by Duncombe[36] using a porous duct, 4 in. internal diameter and $6\frac{3}{16}$ in. long, but with non-permeable sections attached to it on either end; $1\frac{1}{2}$ in. upstream and $3\frac{1}{2}$ in. downstream. The cooling air jacket surrounded all these sections, the coolant flowing first past the non-permeable sections and then into the porous duct. The temperature of the cooling air was measured only at the inlet to the jacket. These experimental conditions make any form of correlation very difficult.

A large scale experiment has been undertaken by Brunk[37] in which a 60 in. × 10 in. × $\frac{1}{2}$ in. thick porous bronze plate was inserted into one wall of a 4 in. × 10 in. wind tunnel, carrying air at a mean Mach number of 0·65. Cooling was achieved by refrigerating the coolant (air). Uniform effusion was aimed at by sectional supplies of coolant and the porous plate was well instrumented with thermocouples. Insufficient data are given in the report to affect an accurate correlation on the basis of Fig. 9, but it would appear that the coolant mass flows are much too large for the measured wall temperatures. It is admitted by Brunk that the porous plate varied greatly in local permeability and this would affect local temperatures. Small errors in measured wall temperature are of great significance for conditions of "over-cooling," *i.e.* large values of ξ.

The only published experimental data for specimens inserted into a hot gas stream (except for those published in this paper) are for gas turbine blades. Two such attempts have been made and in each case a porous gauze shell was wrapped round the fluted stem of the blade. The coolant distribution could be regulated by feeding different quantities to each compartment. Surface temperature measurements were very difficult. Donoughe and Diaguila[38] tested such a blade in an actual turbine, but measured the stem temperature only. Andrews *et al.*[39] carried out static cascade tests, but some of the hot gases entered the porous shell owing to excessive pressure variations around the periphery of the blade. There would appear to be no other published data and none for variable injection to conform with exact theory (with the exception of the abortive attempt by Mickley *et al.*[26]).

4.4. SUMMARY OF EXPERIMENTAL FINDINGS

1. The experiments with the bronze and stainless steel plugs or cylinders have verified the theoretical conclusion that the nature of the porous material has no effect upon the cooling efficiency. The thermal conductivity of the bronze was eight times that of the stainless steel. The pore size distribution must, however, be fine enough to provide a continuous effusing layer, as shown in the work by Glenny[40].

2. The overall mechanism of effusion cooling would seem to be well described by the heat balance theory, postulated in this paper. It can be used as a basis for correlation of measurements made under very different conditions; such as a porous plug set in the wall of a duct, flow through long or short tubes of large or small diameters, or a specimen inserted in a stream of hot gases. Such a correlation is furthermore well defined by the theoretical curve of equation (15). That the same theory should apply to such widely varying conditions is due to the basis upon which the heat

balance was derived. No mechanism had to be defined for the transfer of heat to the porous surfaces (such as conduction or convection, or laminar or turbulent flow). The theory states that for each section of the porous wall a heat balance exists, which is independent from any other section, as far as heat flow is concerned. The structure of the boundary layer with injection is only involved to determine the momentum loss thickness and the simple, one-parameter, law would appear to be adequate for this purpose.

The experiments which are in agreement with the theory covered a Reynolds number range from 3,700 to 200,000 and a main stream temperature range from 255 to 1,500°F. The range covered by the correlation parameter $(G_c/G_0)^2 Re$ is from 0·034 to 25.

3. The cooling mechanism with effusion consists of two parts; the heat abstracted from the porous material by the coolant on passing through it, and the prevention of heat inflow from the main stream by the "blanketing" effect of the effusing layer. The degree of blanketing achieved in the various experiments can be estimated by calculating the surface temperature that would have been attained if only the first part of the mechanism was operative. The heat transfer coefficient under those conditions is then the same as for solid surfaces. The heat balance for the porous plug experiments would then be, assuming that all the heat is absorbed by the coolant and that it attains the surface temperature: —

$$hA_1(T_0 - T_{s1}) = G_c c_p A (T_{s1} - T_c)$$

where

- h heat transfer coefficient for solid surfaces, obtained from the known correlation $Nu = 0{\cdot}02\, Re^{0{\cdot}8}$
- A_1 total exposed area of mounting and plug
- T_0 main stream temperature
- T_{s1} surface temperature without the blanketing effect
- G_c coolant mass flow per unit area
- c_p specific heat of coolant
- A cross-sectional area of plug
- T_c inlet temperature of coolant.

A similar heat balance can be set up for the porous cylinders, the heat transfer coefficient being determined from the equation for forced convection over solid tubes: —

$$Nu = 0{\cdot}24\, Re^{0{\cdot}6}$$

in which the physical properties are based on the mean film temperature[41]. The results by Bayley can also be assessed on this basis[42]. The derived temperature ratio $(T_0 - T_{s1})/(T_0 - T_c)$ has been plotted against the measured ratio $(T_0 - T_s)/(T_0 - T_c)$ in Fig. 10. Any results below the dividing line would indicate an absence of any "blanketing" effect. It is seen that all the points are either on or above this line. The effusing layer therefore provides a definite degree of heat insulation or blanketing.

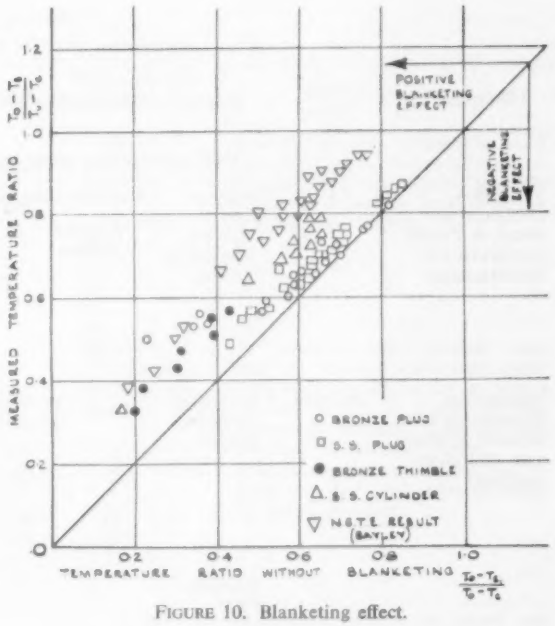


FIGURE 10. Blanketing effect.

5. Porous Materials and Specific Applications

It is an essential feature of this method of cooling that the coolant emerges out of the surface to form a continuous layer of insulation between the surface and the heat source. The efficiency of cooling is therefore influenced by the nature of the porous material when the size and distribution of the apertures is such that the continuous layer fails to form. Perforated sheet and some types of non-uniform gauzes are apt to have the coolant emerge as a series of discrete jets which enter into and mix with the main stream of hot gases and much of the heat insulation effect is thereby lost. The openings of the pores should be divergent outwards and closely spaced together as with a packing of small spheres or square mesh gauze made from circular wire. Glenny[40] has given a thorough assessment of the merits of a variety of different porous materials. Some details of porous materials commercially available are listed in Table II; the list is not necessarily complete, but gives a representative analysis of the present position.

5.1. POROUS METALS MADE BY POWDER METALLURGY METHODS

There are principally two methods suitable for making porous components from metal powders.

5.1.1. *By Cold Compacting Graded Powder in a Die at High Pressure followed by Sintering*

This can give a finished component of the required size. Cooling passages in the interior of the component can be provided by the introduction of low melting point metal wires which are evaporated out during the sintering operation. The porosity of the compact can be controlled by choice of particle size and compacting pressure[43, 44]. Further control over the porosity can be achieved by mixing with the metal powder a certain amount of graded non-metallic volatile filler, such as

TABLE II

Manufacturer	*Trade Name*	*Material*	*Tensile Strength Properties*	*Maximum Size of Component*	*Remarks*
POROUS MATERIALS MADE BY POWDER METALLURGY TECHNIQUES					
The B.S.A. Company and Metal & Plastic Compacts Ltd. (Birmingham)	—	Stainless Steel, Nimonic type alloys, Stellites	Stainless Steel (electrolytic) Porosity per cent. / U.T.S. lb./in.² 10 / 67,000 20 / 38,000 30 / 20,000 40 / 10,000	Sheet 24 in. × 24 in.	Powders now also being made by the atomising process; filters and have made porous turbine blades, *see* Fig. 16. Stainless steel was used in the experiments with cylinders.
Sheepbridge Engineering also Sintered Products Ltd. (Sutton-in-Ashfield)	Porosint	Bronze by atomising process	Grade / Porosity per cent. / U.T.S. lb./in.² A / 22 / 8,000 B / 33 / 8,000 C / 35 / 6,700 D / 38 / 6,000 E / 35 / 5,000	Sheet 20 in. × 12 in.	Porosint was used in the effusion cooling experiments, filters. Porosint and stainless steel used for de-icing applications in conjunction with T.K.S. (Aircraft De-Icing) Ltd. Capacity for sheet size to be enlarged.
	—	Stainless Steel	—	Sheet 9 in. × 4 in.	
Bound Brook Bearings Ltd. (Lichfield)	—	Bronze, Iron-Copper Alloys	—	Sheet 15 in. × 15 in. discs 6 in. diam.	Bronze filters in a wide variety of sizes.
Powdercraft (S. Carolina)	—	Bronze	—	Plate 72 in. × 14 in. × ¼ in.	Large plate used for experiments of Ref. 37.
The Pall Filtration Co., also Micro Metallic Corp. (New York)	P.S.S.	Stainless Steel (several types) Nickel Monel Stellite	Porous Stainless Steel Grade / Approx. Porosity per cent. / Tensile Strength lb./in.² C / 55 / 6,000 D / 50 / 9,000 E / 50 / 15,000 F / 50 / 15,000 G / 50 / 15,000 H / 45 / 15,000 X / 20 / 25,000	Sheet max. (special) 72 in. × 18 in. Standard 48 in. × 18 in.	Grade X most suitable for effusion cooling. Max. U.T.S. reported at 40,000 lb./in.² Elongation 3-8 per cent. Approx. modules of elasticity 15 × 10^6 lb./in.² Mean pore opening 15 microns. Minimum thickness 0·020 in.
POROUS MATERIALS FROM WOVEN WIRE					
N. Greening & Sons (Warrington)	—	Mild Steel, Stainless Steel, Non-Ferrous Metals	—	100 ft. rolls max. width 48 in.	Variety of weaves. Square mesh from 2 to 300/in. Twilled weave and Hollander cloth.
G. A. Harvey & Co. (London)	—	Non-Ferrous, Steel, Stainless Steel, Heat Resisting Alloys	—	100 ft. rolls max. width 72 in.	Double crimped square mesh from 2 to 120/in. Twilled weave to 200/in. Also Hollander cloth and rolled gauze.
Lockers (Wire Weavers) Ltd. (Warrington)	Durite	Non-Ferrous, Steel, Stainless Steel, Immaculate 5, 37/18 Ni-Cr	—	100 ft. rolls max. width 48 in.	Variety of weaves. Mesh sizes 2 to 400/in. Twilled weave and Hollander cloth.

TABLE II (*continued*)

POROUS MATERIALS FROM WOVEN WIRE (*continued*)

Manufacturer	*Trade Name*	*Material*	*Tensile Strength Properties*	*Maximum Size of Component*	*Remarks*
The Pall Filtration Co., also Aircraft Porous Media Inc. (New York)	Rigimesh	Stainless Steels (several types) Alloy N-155, Stellite, Inconel, Monel	Stainless Steel Temp. °F / U.T.S. lb./in.² / Elongation per cent. 60 / 37,400 / 8·7 1,500 / 22,000 / 5·5 1,650 / 13,400 / 0·8	Sheet max. (special) 72 in. × 18 in. Standard 48 in. × 18 in.	A woven material, sintered to weld warp and weft at points of contact, in more than one layer. Strength properties dependent upon direction of application of load.
Poroloy Equipment Inc. (California) Bendix Aviation Corp. (Filter Div., Detroit)	Poroloy	Non-Ferous, Stainless Steel, Alloy N-155, Haymes Alloy 25	Stainless Steel 35° Crossover Angle Porosity per cent. / U.T.S. max. / lb./in.² min. 53 / 25,000 / 3,500 38 / 35,000 / 6,000 27 / 45,000 / 10,000 20 / 55,000 / 13,000 15 / 65,000 / 18,000 11 / 78,000 / 30,000	Sheets:— 56 in. × 24 in. Thickness:— 0·015 in. to 0·125 in. Cylinders:— $\frac{1}{16}$ in. i.d. × 6 in. L. to 18 in. diam. × 24 in. L.	A wrapped and sintered wire material, woven continuously, either with wires at right angles or with a reduced crossover angle to give directional strength. Cylinders are seamless; also in cone shapes. Used for turbine blades, *see* Fig. 17. Used also for combustion chamber liners and jet tubes.
PERFORATED SHEET					
N. Greening & Sons (Warrington)	—	Most metals available in sheet form	—	Sheet (less than 12g) 120 in. × 48 in. Plate ($\frac{1}{4}$ in.–$\frac{1}{2}$ in.) 144 in. × 60 in.	Hole sizes from 6 in. round and square down to 0·026 in. round.
BLC Porous Materials Co. (California)	Varaperf	Most metals available in sheet form	—	Sheet, max. Standard 120 in. × 29 in.	Used as backing sheets for Varapac; *see below* "Fibre Base Porous Materials."
The Harrington & King Perforating Co. (Chicago)	—	Most materials available in sheet form	—	Standard 120 in. × 48 in.	Have made perforated sheet in stainless steel of 250 ft. length. Min. diam. of hole 0·020 in.
Charles Mundt & Sons (New York)	—	Most materials available in sheet form	—	—	Min. diam. of hole 0·018 in.
ELECTROFORMED SHEET					
N. Greening & Sons (Warrington)	Perflex	Nickel, Copper, Nickel clad Copper	—	Sheet Standard 24 in. × 24 in. to be increased to 100 ft. × 36 in.	Standard count ranges:— 25 × 25/in. (0·022 in. d.), 0·010 in. thick; 80 × 80/in. (0·004 in. d.), 0·004 in. thick. Special down to 300 × 300/in., 0·002 in. thick, 12 in. × 12 in.
The C. O. Jelliff Mfg. Corp. (Connecticut)	Lektromesh	Copper, Nickel clad Copper	—	Sheet Standard counts 25 in. × 25 in. to 100 in. × 100 in. in 100 ft. × 36 in.	Special count ranges:— 200 × 200/in. in 13 in. × 13 in. 400 × 400/in. in 6 in. × 6 in.
FIBRE BASE POROUS MATERIALS					
The Chrome Alloying Co. Ltd. (Hatfield)	—	Steel Wool	—	Disc 4 in. diam.	Steel wool, compacted, sintered and chromised, very permeable.
BLC Porous Materials Co. (California)	Varapac	Fibreglas	—	Sheet, max. standard 120 in. × 29 in.	Fibreglas sandwiched between sheets of perforated metal can withstand 2,000°F. Used as combustion chamber liner.

ammonium carbonate[44, 45, 46]. The filler gasifies on sintering and small passages are created connecting the initial voids. The size and number of voids and interconnecting passages can be controlled to a certain degree by the relative proportions and sizes of metallic and non-metallic powders.

As can be seen from Table II the mechanical strength of compacts of low porosity is sufficient for low stressed components although more data are required for the strength at elevated temperatures. Surprisingly enough, the fatigue properties of porous, sintered metals are not so much impaired by the porous structure as might at first be feared[47, 48]. A limiting condition for this method can be the size of die and the compacting pressure, although the cold rolling of metal powder into sheet[49] is a means for overcoming this difficulty.

5.1.2. *Large Porous Sheets Made by Sintering Loose Powder without Any Prior Compacting*[50]

The strength of such sheet is clearly less than that of compacted material and the porosity greater. A high porosity is generally not required for effusion cooling and such sheets can be stiffened by cold pressing after sintering (calendering) or by cold rolling followed by a second sintering process. The grade X made by Micro-Metallic Corporation, given in Table II, is made in this manner and the increase in strength over the other grades is considerable.

5.2. POROUS MATERIALS BUILT UP FROM WOVEN WIRE

Porous components can be made from wire gauzes or formed into prescribed shapes by special techniques of weaving. Details are given in Table II of representative types of standard gauze materials and it should be noticed that the continuous length available (rolls of 100 ft.) removes practically any limitation in size. Nearly all materials that are available in wire form can be woven into gauzes and the corrosion and heat resisting properties of the gauze are similar to those of the actual metal. The strength of a gauze depends upon the direction of application of the load and upon the cross-over angle between the warp and the weft. Equal loads applied at right angles give rise to equal stresses for a cross-over angle of 90°, but an increase in ultimate stress in one direction can be obtained by reducing this angle. This is shown, for example, for a cross-over angle of 35° for a woven material made by Poroloy Equipment Inc. (*see* Table II). Use of this characteristic in design of highly stressed porous components can overcome the usual stress limitations of porous materials. More strength data for wire cloth are to be found in Ref. 51.

A single gauze is generally too permeable for effusion cooling, but this can be reduced by cold rolling. Rigidity of component can be achieved by brazing the gauze to a honeycomb backing frame or by building up a porous sheet out of several layers of gauze which are sintered together at the points of contact of the wires. Many layers of gauze can be formed into one sheet in this manner and the permeability controlled by suitable choice of the mesh size and wire diameter of the individual layers [12, 29, 52]. Another method for joining layers of gauze together is by coating the wires with a lower melting point metal and brazing[40]. The permeability of the sintered gauzes can be controlled further by cold rolling followed by a second sinter.

The high permeability, *i.e.* large flow through the gauze for a small pressure drop, coupled with a potentially high strength at high temperatures, makes the sintered gauzes more attractive as compared with powder metallurgy materials where a high strength usually implies a low permeability, *i.e.* large pressure drop for a small flow.

5.3. OTHER TYPES OF POROUS MATERIALS

Porous sheets can be made by mechanically perforating solid sheet, but the smallest size of hole and the spacing are usually too large for an efficient direct application for effusion cooling[40, 53]. The building up of a grid of metal by electrodeposition provides great uniformity, but the denser spacings can only be built up into very thin sheets. These materials are useful for secondary purposes, either as backing sheets or for metering the flow of coolant. Another type of porous material can be formed out of metal or fibre glass wool[54] contained as a sandwich between sheets of perforated metal or gauzes. Examples of these several types of material are given in Table II.

Porous ceramics could also be used for effusion cooling, the advantages being that a higher temperature level than with most metals can be tolerated and that a failure of coolant supply need not be disastrous instantly. The disadvantage of most ceramics of mechanical failure due to thermal shock can be minimised by ensuring an adequate supply of coolant at starting up and maintaining the supply after shut down. The coolant within the ceramic will also contribute to the heat inertia. Porous ceramics have been developed for filters and for diffusers of gases in liquids.

5.4. CLOGGING AND DEPOSITION

It is undisputed that the porous materials most suited for effusion cooling are also highly efficient filters and are apt to collect any foreign matter contained in the coolant. This is unavoidable and the coolant must be passed through a filter if operation for any considerable length of time is anticipated. The provision of a filter in the coolant supply line is perhaps only a small part, considering the inevitable complexity that will arise with any cooling system. It should be remembered that, with internal cooling where air is forced through very small holes, filtering is also considered necessary. A compromise can be achieved for short duration operation by choosing a porous material slightly less efficient from both the cooling and filtering angles. It may also be that a hot porous metal is less efficient as a filter than when cold, but more research into the mechanism of hot filtration is required.

It might be argued that clogging of the pores will also occur on the outlet side of the porous surface due to deposition of solids fom the main stream of hot combustion products as in, for example, a gas turbine burning heavy fuel oil. This would not appear to be so serious as the following test results indicate. One of the porous stainless steel cylinders used in the experiments described in Section 4 was exposed

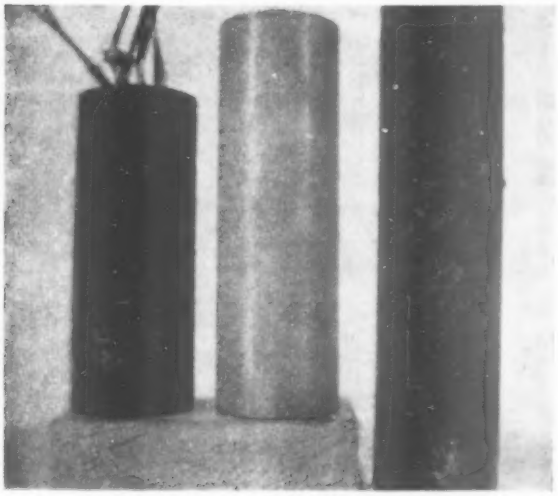


FIGURE 11. Comparison of porous and non-porous stainless steel cylinders exposed to corrosive hot gases.

FIGURE 12. Comparison of porous and non-porous stainless steel cylinders exposed to the exhaust from a peat burning combustion chamber.

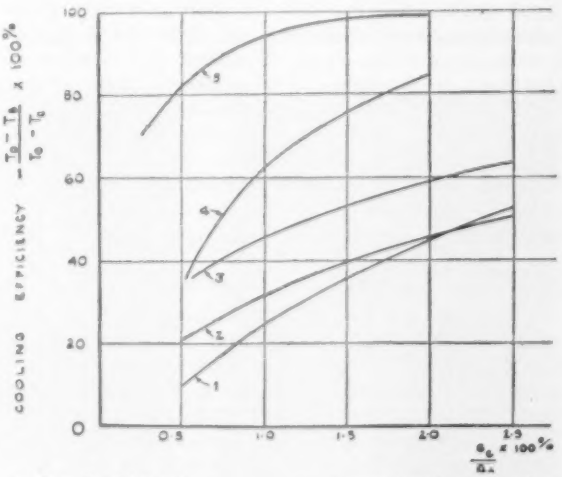
continuously for 150 hours to the products of combustion of a heavy fuel oil burning deposition rig. The main stream temperature was about 1,500°F. and the maximum surface temperature 1,000°F. A companion solid stainless steel tube, of the same diameter and cooled internally also to 1,000°F., had been placed along-side the porous specimen for the same length of time. A considerable amount of scaling and some deposition were observed on the solid tube whereas none could be detected on the porous specimen except for discolouring.

The photograph in Fig. 11 shows the solid tube on the right, a new porous specimen in the centre and the exposed porous cylinder on the left. A cold flow test showed that the permeability had decreased by about 10 per cent, but this may have been due partially to oxidation, a surface temperature of 1,000°F. being too high for stainless steel to resist attack by oxidation even under normal conditions. This result supports the contention that the effusion created a continuous layer flowing away from the surface and that mixing with the main stream took place remote from the surface. The offending sodium and vanadium vapours condensed within the effusing layer and were thus carried back into the main stream, instead of condensing on the cooled surface. No sticky agents were therefore formed on the surface to which any ash particles could have adhered. That this did happen on a solid surface was evident from the companion tube.

Another experiment was carried out in conjunction with Ruston and Hornsby Ltd. in which similar stainless steel tubes, one porous and one solid, were inserted into the outlet from an experimental peat burning combustion chamber before the ash separator. The gas temperature varied between 1,300 and 1,750°F. and the surface temperatures of both tubes were kept at 265-570°F. The experiment lasted about 20 hours. A photograph of the tubes is shown in Fig. 12 with the porous on the right and the solid on the left. The effect of ash deposition on the solid tube is clearly visible, but none could be found on the porous tube nor was there any change in the cold flow permeability.

5.5. APPLICATION TO COMBUSTION CHAMBERS FOR GAS TURBINES AND ROCKET MOTORS

The inner linings of combustion chambers are exposed to high heat fluxes and have to be cooled. The cooling should be uniform to avoid buckling due to thermal stressing. The nominal stress in the lining is not great as the outer lining acts as a pressure casing, the space between the inner and outer shells being filled



1. Localised injection.
2. External air circulation.
3. Combustion of 1 and 2.
4. Louvred wall construction.
5. Effusion cooling.

FIGURE 13. Comparison of several methods of cooling.

with secondary and cooling air. The inner lining can be cooled in a variety of ways and a comparison of several of such methods, based partially on experiment and calculation, has been carried out by Bayley[55] and is given in Fig. 13 as the cooling efficiency to a basis of cooling air mass flow as a percentage of main stream flow. It is at once apparent that far less cooling air per unit area is needed with effusion cooling than with any other method. The effusion cooling graph is based on the results by Bayley correlated in Fig. 9. The temperature efficiency ratio was based on the maximum expected wall temperature and it is of interest to notice that film cooling by injection through discrete holes, spaced apart, is the worst of all when compared on this basis, as most of the cooling air is lost.

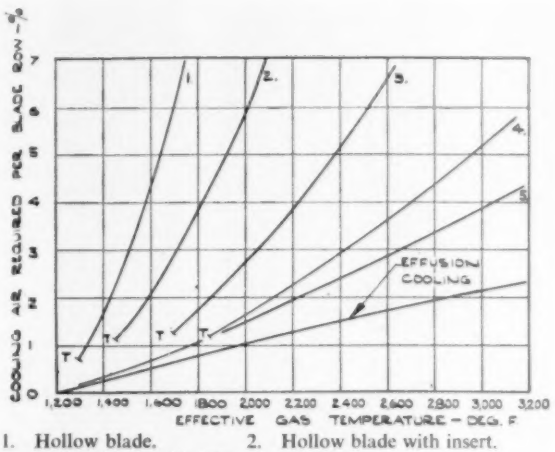
Large porous liners are best made from a woven wire material, rolled to control the permeability and stiffened with brazed on backing grids. Grading of the wire sizes or degrees of thickness reduction during rolling can ensure that the right amounts of cooling air are injected at the right places. Woven wire sheets can be welded readily to solid flanges.

The capacity of transpiration cooled liners to cope with local hot spots depends upon the type of cooling fluid used. The local increase in heat flux raises the wall temperature and because of the change of viscosity with temperature a gaseous coolant flow would be reduced, thereby aggravating the hot spot, but the reverse occurs with a liquid coolant; the greater the heat flux the greater the flow of liquid for a given pressure drop. If, however, the local heat flux is so great as to cause the liquid to boil within the porous wall then instability in coolant flow will occur with a similar aggravation as with gases. The overload capacity of porous liners for unexpected increases of heat flux has therefore to be determined by experiment.

Boiling of a liquid coolant within the porous wall can occur when heat is transmitted through the thin liquid film on the surface by radiation. Excessive heat input by radiation is likely to occur in rocket combustion chambers and nozzles and particular emphasis is to be given in the choice of coolant, or propellant if also used, to the infra-red absorptivity. One of the best liquids for absorbing radiation is water, a film as thin as 0·004 in. being practically alike to a black body with respect to infra-red radiation. It may, therefore, be more advantageous in sweat cooling rocket motors to use an additional liquid like water in small quantities than the propellant in much larger quantities.

5.6. APPLICATION TO GAS TURBINE BLADES

A comparison has been made by Brown[56] of the merits of several types of internal air cooling and of effusion cooling for the same blade profile and flow conditions. The result is given in Fig. 14 and the most efficient method is undoubtedly effusion cooling. The internal cooling method approaching this most nearly is number five, a solid blade with few holes with inserts to increase the heat transfer coefficient on the coolant side. There is a limit to the reduction in mass flow for the internal methods whereby the coolant spills out at the tip of the blade, in that the temperature



1. Hollow blade. 2. Hollow blade with insert.
3. Hollow blade with internal cooling fins.
4. Solid blade with a large number of small holes.
5. Solid blade with a few holes with inserts.

Blade temperature: (*a*) effusion cooling 1,200°F; (*b*) internal cooling—to give the same life as for a blade with a uniform temperature of 1,200°F.

Cooling-air inlet temperature, 120°F; blade aspect ratio, 2·5; pitch/chord ratio, 0·7; gas-outlet angle, 60 deg. relative to axial direction; *T*, Reynolds number for flow in cooling-air passages reaches, 2,500.

FIGURE 14. Estimated flow of cooling air required for different cooling arrangements at various temperatures, expressed as percentage of engine throughput.

of the coolant is raised to such high levels in its passage through the blade to be of little use for cooling the blade tip. The likelihood of a similar limitation with effusion cooling is much less as the heat is returned to the source at each section.

The return of heat to the working fluid all along the blade leads to a further distinction of the effusion method over all other methods in that the coolant having mixed with and attained the temperature of the working fluid, which it must do within the boundary layer since heat is conducted through it, can do work in succeeding stages of blading. The only coolant energy loss is therefore part of the work that could have been done by expansion in the stage in which the coolant is injected. This is in fact very small compared with the total work done. Allowance for this should be made when comparing outputs from cooled and uncooled turbines.

As an example, some calculations were made for a turbine cycle with a pressure ratio of $2\frac{1}{2}:1$, 50 per cent reaction, turbine blade efficiency of 86 per cent, compressor efficiency of 87 per cent and an inlet gas temperature of 2,200°F. The loss in net power produced by the effusion cooled turbine compared with the power produced by an uncooled turbine was $\frac{1}{2}$ per cent with a cooling air flow of one per cent per blade ring and $2\frac{1}{2}$ per cent with 5 per cent cooling air. These are only paper losses as it is not yet a practical proposition to operate an uncooled turbine with a gas temperature of 2,200°F. A fairer basis for comparison is on equal quantities of fuel burned and adjusting the air throughput accordingly. The inlet temperature for the effusion-cooled turbine was again taken at 2,200°F.,

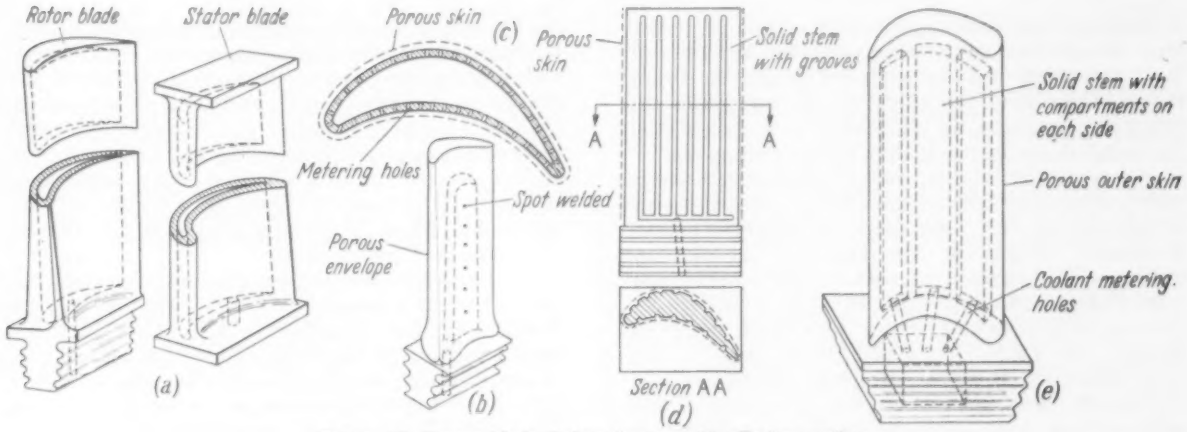


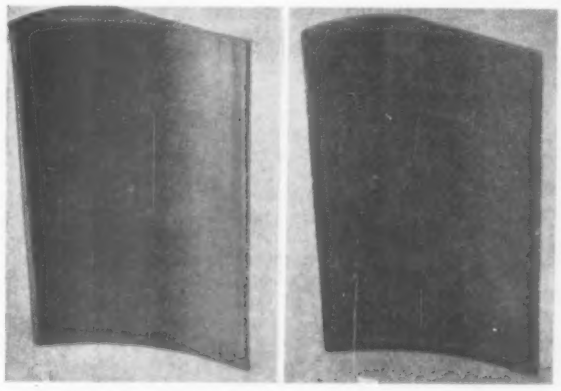
FIGURE 15. Porous blade designs for use with effusion cooling.

but for the uncooled turbine at 1,550°F. The total amount of net power produced by the uncooled turbine was nearly 10 per cent less than the power produced by the cooled turbine, the "loss" now being with the uncooled cycle. The ability of the coolant to contribute substantially to the expansion work in the effusion-cooling method is an additional advantage and a somewhat generous coolant flow can thus be tolerated[57, 58].

Some designs of blades with porous surfaces are illustrated in Fig. 15. The simplest design, shown in Fig. 15(*a*), consists of a porous blade made throughout by powder metallurgy methods and shaped in a hollow form, the coolant being supplied at the same pressure at all points. Such a design is not likely to produce a very strong blade as the wall has to be thin and rather porous owing to the small pressure differential generally available. Preferential distribution of the coolant could be achieved by varying the permeability of the wall. It is clearly better to separate the load carrying and the coolant distribution function.

A design to achieve this is shown in Fig. 15(*b*) consisting of a solid stem, integral with the root to act as a load carrier to which a porous shell is spot welded. Alternatively, a sheet metal construction is shown in Fig. 15(*c*) in which a porous skin is sintered to a hollow blade formed out of perforated sheet. Spacing of the perforations would assist to give a non-uniform coolant distribution. Even more control of the coolant distribution can be obtained with the design shown in Fig. 15(*d*) in which a porous skin is sintered to a solid stem, shaped in blade form and having a pattern of grooves or channels on its surface through which the coolant is forced from a common gully in the root. The spacing and size of the grooves will enable any desired coolant distribution to be obtained. The porous layer could be sintered to the stem in a die under pressure, the grooves being filled with a volatile substance which on evaporating would force out through the pores, thus ensuring that there were through connections. The size of the grooves can be reduced towards the tip of the blade by tapering to reduce the coolant flow. The stresses are progressively reduced towards the tip allowing a correspondingly higher blade temperature to be tolerated for the same rate of creep as in the more highly stressed root section.

Another type of fabricated blade is shown in Fig. 15(*e*) where a porous outer skin made, for example, from a woven wire material, is attached to a stem, sub-divided into several compartments to each of which a supply of coolant is metered separately. A blade of this construction was used in the experimental work of Ref. 39. It is absolutely essential to ensure that the



(*a*) (*b*)

FIGURE 16. Finished machined, porous stainless steel blade. (*a*) before etching; (*b*) after etching, with 111 holes, 0·020 in. diameter. (Reprinted from "Symposium on Powder Metallurgy, 1954." *Courtesy of the Iron and Steel Institute.*)

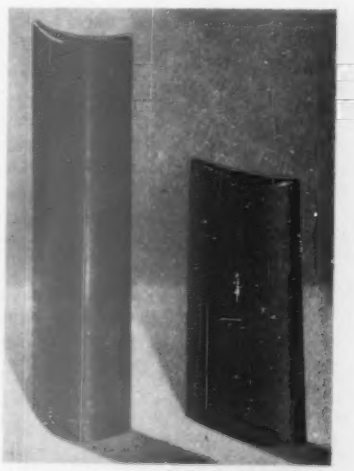


FIGURE 17. Porous stainless steel blades made from woven wire.

coolant pressure within each compartment is greater than the surrounding pressure otherwise hot gas will flow inwards through the porous skin with disastrous results. The more numerous the compartments the better for regulating the distributed flow coolant and the design shown in Fig. 15(*d*) is the most promising.

An example[44] of some porous stainless steel blades with a number of longitudinal holes for coolant supply is shown in Fig. 16. These were machined from porous rectangular blocks and the porosity reinstated by etching. The photographs show a blade before and after etching. Another example is given in Fig. 17, showing a continuously woven wire blade made by Poroloy (*see* Table II). There are no seams in this construction and it would seem most suitable for spot welding to a solid stem. Such fabricated construction using woven wire materials would be expected to have high internal damping and thereby resist the building up of excessive vibrations.

5.7. APPLICATION TO SURFACES EXPOSED TO AERODYNAMIC HEATING

The effusion or sweat cooling of parts of the thrust producing motors has been dealt with in Sections 5.5 and 5.6, but the temperature of the actual flying vehicle is raised considerably when travelling at very high speeds due to aerodynamic heating. When cooling of the outside skin becomes necessary it is clearly essential to use the most economical method possible owing to the large surface area. Sweat cooling, *i.e.* allowing a liquid to percolate through the surface is a possibility, particularly when it is remembered that the heating of *dry* surfaces by friction in the boundary layer is aggravated by an increase in relative velocities but that a *wet* surface is cooled by evaporation on passing a stream of air over it and this cooling is the more intense the faster, hotter and dryer the air stream and the lower the pressure[59, 60, 61].

The aerodynamic characteristics of the boundary layer can be favourably influenced by cooling. A surface cooler than the average boundary layer temperature can delay transition on account of the increase in viscosity of most gases with temperature[62]. The effects due to aerodynamic heating can be further reduced by injecting into the boundary layer a light-weight gas such as hydrogen[63]. The skin friction and heat transfer to a flat plate can be reduced considerably with the injection of only about 20 per cent as much hydrogen or about 40 per cent as much helium as with the injection of air[64].

Several of the materials listed in Table II could be used for this purpose. It has been reported[65] that the Russians have solved the re-entry problem of the I.C.B.M. by sweat-cooling the skin of the warhead by forcing a liquid under high pressure through a porous metal-ceramic, consisting of a mixture of a special fireproof clay and between 10 and 20 per cent of powdered cobalt.

6. Conclusions

The heat balance method of analysis of the effusion cooling process has given a form of correlation agreeing closely with most of the known experimental results. It is thus possible to estimate the coolant flow requirements for most practical applications in which the effusion rate is approximately uniform along the surface. Caution is required, however, in those instances where the rate of potential heat input varies greatly along the surface, thereby requiring a corresponding variation in coolant flow although the application of the analysis, section by section, would give a conservative estimate of the required coolant flow.

The application of effusion or sweat cooling has been shown to be practicable for all the hot parts of gas turbines and rocket motors, or for cooling the flying vehicle itself. The variety of porous materials available is large although much further development is needed, particularly for the application to rotor blades, requiring most probably a composite construction of a solid stem with a porous shell attached and with metered supplies of coolant to a number of sections, like the designs shown in Figs. 15 (*d*) and (*e*). Attention must be paid to filtering the coolant, but experiments have shown that clogging of the pores on the heat exposed side need not be so serious as was first thought.

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Residual Stresses Resulting from the Forming of High Strength Aluminium Alloys

by

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SUMMARY: An X-ray back reflection technique has been used to measure the surface residual stresses resulting from the cold and hot forming of certain high strength aluminium alloys. The alloys examined were to specifications DTD 683, DTD 687 and B.S.S. L65, and the residual stresses have been related to the residual strain in bending of these alloys. The results show that, apart from the degree of straining, the residual stresses are affected by the heat treatment (cold or hot quench) and the amount (if any) of controlled stretching that the alloy has had between solution treatment and precipitation.

1. Introduction

Residual stresses result in consequence of non-uniform plastic deformation, which, from the point of view of this paper is caused by quenching and forming to a permanent set.

Quenching stresses are dependent upon the size of the section and the temperature of the quenching media, and are characterised by surface compressive and internal tensile stresses; for example, cold water quenching of one inch sections, results, after artificial ageing, in surface stresses of the order -8 to -10 tons/in.^{2}, whereas a hot water quench (85°C) results in surface stresses of the order -1 to -3 tons/in.^{2}. A cold water quench on sheet material (sections smaller than 12 S.W.G.) also results in surface stresses of the low order -1 to -3 tons/in.^{2}, due to the considerably smaller section.

When a beam is formed, and is still under the bending load, the outer fibres of the beam have yielded plastically on both the tension and the compression faces. When the beam is released from the bending moment, elastic springback occurs and the final stress distribution through the beam is a compressive stress on the tension face and a tensile stress on the compression face, having changed sign three times through the section.[1] The value of these residual stresses depends largely on the mechanical properties of the material at the time of bending, by the degree of the bend, and the geometry of the section.

Controlled stretching of cold water quenched, high strength aluminium alloys results in a reduction of the quenching stresses, these being then further reduced by artificial ageing or precipitation.

The work reported here has correlated the residual surface stresses with the surface residual strain of the following high strength aluminium alloys; specifications DTD 683, DTD 687 and B.S.S. L65. The forming of the alloys was carried out cold, in the solution-treated condition, the fully heat-treated condition and, in certain cases, after controlled stretching and at elevated temperature.

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2. Procedure

2.1. DTD 683 EXTRUDED BAR

The test pieces used for bending and subsequent X-ray stress analysis consisted of 12 in. × 1 in. × 1 in. square section bars machined from the centre of a NORAL 2 in. diameter DTD 683 extrusion.

The bars scheduled for cold forming in the solution-treated condition were heat-treated as follows, 45 minutes at 465°C, and quenched into hot water at 85°C. Forming was carried out 2 hours, 6 hours and in one instance 10 months after quenching, under conditions of four point loading. The test bars were then artificially aged for 16 hours at 135°C. The resulting values of the longitudinal stress, on both the tension and the compression faces, for varying degrees of strain, were determined, using a multi-exposure X-ray back reflection technique.[2]

The procedure adopted for the investigation on fully heat-treated material was as follows; the test bars were solution-treated and artificially aged, times and temperatures as stated. Cold forming and stress analysis followed. Some of these bars were also hot formed at a temperature of 140°C ± 2°, the cycle of events for each bar, after full heat treatment, then being: an initial soaking period of 15 minutes in oil at 140°C (this time being necessary for uniform temperature distribution through a one inch square section); with the bar and bending rig still immersed in the oil, forming to the required degree was completed within the next 30 minutes ±10 (total time at 140°C had also been shown not to produce any deleterious effects on the mechanical properties). On completion of forming, the bars were removed from the oil and allowed to cool to room temperature, residual stress measurements were then carried out.

Two bars were annealed; 2 hours at 380°C, furnace cooled to 300°C and then air cooled to room temperature. Cold forming was then carried out followed by solution-treatment, artificial ageing (as previously mentioned) and finally residual stress measurements.

To complete the programme on DTD 683 material, a number of test bars were solution-treated, with a cold water quench; the bars were then controlled stretched to

a permanent elongation of 1·5 per cent within 4 hours of quenching and then artificially aged. These bars were then cold formed and the resulting residual stresses determined.

2.2. DTD 687 SHEET

The sheet test pieces consisted of 1 in. strips cut in the longitudinal direction from an "as received" 12 S.W.G. sheet to DTD 687 specification.

The strips scheduled for cold forming in the solution-treated condition were heat-treated as follows: 30 minutes at 465°C and quenched into cold water. Forming was carried out (*a*) 2 hours and (*b*) 6 hours after quenching by loading the strip via the appropriate diameter former into a lead block. The extent of straining was calculated after springback and was related to the residual bend radius in terms of sheet thickness, also, as a percentage residual strain. The test strips were then artificially aged for 16 hours at 135°C. Before residual stress measurements were carried out, the cladding on the sheet material was removed by dry polishing with emery papers and etching with mixed acids, since a stress measurement taken on the very low strength cladding would be of a low order and not typical of the stresses in the high strength core. The resulting values of the longitudinal stresses on the tension faces were determined as described above, the corresponding stresses on the compression face being in most cases difficult to measure due to the shadowing effect of the bent strip itself.

Finally, a series of DTD 687 strips were fully heat-treated; times and temperatures for solution-treatment and artificial ageing being the same as in the foregoing paragraph. Cold forming, removal of cladding and residual stress measurements were similarly carried out.

2.3. B.S.S. L65 EXTRUDED BAR

The test pieces used for bending and subsequent X-ray stress analysis consisted of 12 in. × 1 in. × 1 in. square section bars machined from the centre of a NORAL 2 in. diameter L65 extrusion.

The bars scheduled for cold forming in the solution-treated condition were heat-treated as follows: 45 minutes at 510°C and quenched into cold water. Cold forming was carried out (*a*) 2 hours and (*b*) 6 hours after quenching, under conditions of four point loading. The test bars were then artificially aged for 16 hours at 170°C. The resulting values of the longitudinal stress, on both the tension and the compression faces, for varying degrees of strain were determined.

For the investigation on cold forming L65 in the fully heat-treated condition, the test bars were solution-treated and artificially aged as in the foregoing paragraph. Then, residual strain and residual stresses resulting from the cold forming operation were correlated as before.

Finally, some of the bars were controlled stretched to a permanent elongation of 1·5 per cent within 4 hours of quenching and then artificially aged. Cold forming and residual stress measurements were carried out.

3. Results

The stress measurements given in Table I are in tons/in.², and the normal sign convention has been used, *i.e.* positive for tensile stresses and negative for compressive stresses.

The accuracy of the X-ray stress measurement has been previously discussed[12], but may be briefly outlined here; measurements of the order 10 to 12 tons/in.² are correct to within ±1·0 ton/in.² and values below about 3 tons/in.² are correct to within ±0·3 tons/in.².

The majority of the results given in Table I for DTD 683 and L65 have been presented in graphical form in Figs. 1 and 2 respectively.

4. Discussion of Results

From the results and their graphical interpretation, a reliable estimate may be made of the residual stresses resulting from the forming of these alloys. Also, as will be indicated later, this estimation can be slightly extended to either a variance in heat treatment or another high strength aluminium alloy. It should be noted however, that the four point loading method of bending has been used on extruded bars and that three point loading would tend to shift the neutral axis of the bent beam towards the compression face; secondly, the results should not be used to evaluate the stresses resulting from "stretch-forming" operations.

4.1. DTD 683 EXTRUDED BAR

The results shown in Fig. 1 require very little further explanation. Four of the five curves have been derived from hot water quenched bar, so that the initial surface stress is of the order of −2 tons/in.² and the curves are approximately symmetrical about this stress level, although at higher strains (above 1·0 per cent) this effect is less evident. The fifth curve (*E*) corresponding to controlled stretched material was derived from 1 in. square section bars which were initially cold water quenched, resulting in surface stresses of the order −12 to −14 tons/in.², controlled stretching reduced these stresses to about −3 tons/in.² and artificial ageing finally reduced them to about −2 tons/in.². These stresses on curve *E* are only slightly lower at 1·0 per cent strain than the corresponding stresses resulting from forming DTD 683 material in the fully heat treated condition, but with a cold quench and no controlled stretching. This curve is not shown in Fig. 1, but typical co-ordinates have been shown to be: zero strain, −10 tons/in.²: 1·0 per cent strain, +14 and −16 tons/in.². The prime reason for the higher stresses on curve *E*, in comparison with the other curves, is that slightly higher properties result from the cold quench than from a hot quench. These mechanical properties, however, are within specification requirements, as indeed, are the properties obtained from all heat treatments discussed in this paper.

A programme of more practical significance would be: solution-treat (cold quench), control stretch, form and then artificially age (or precipitate). It is anticipated that the resulting stresses would be considerably below those reported for curve *E*, due (*a*) to lower

TABLE 1

RESIDUAL STRESSES RESULTING FROM THE BENDING UNDER VARIOUS CONDITIONS OF THE FOLLOWING HIGH STRENGTH ALUMINIUM ALLOYS, DTD 683, DTD 687 AND L65.

Material	*Residual Strain per cent*	*Condition of Test Section at time of forming*	*Treatment after forming*	*Residual Stress on compression face*			*Residual Stress on tension face*		
DTD 683	Zero	2 hours after solution	Artificially aged		−1·5		−2·8		
	0·2	treatment	,,		+6·1			−8·6	
	0·5	(85°C quench)	,,		+5·1			−7·4	
	1·0	(cold forming)	,,	+7·2		+7·3	−7·8		−7·4
	3·0	,,	,,	+8·5		+8·2	−7·4		−8·4
	9·0	,,	,,	+5·8		+4·2	−6·2		−4·9
	0·2	6 hours after solution	Artificially aged		+5·5			−8·6	
	0·5	treatment	,,		+6·5			−7·7	
	1·0	(85°C quench)	,,	+6·7		+7·5	−8·9		−8·7
	3·0	(cold forming)	,,	+6·8		+6·0	−8·3		−7·2
	3·0	10 months after solution	None	+13·8		+13·4			
	3·0	treatment (85°C quench) (cold forming)	Artificially aged	+9·8		+7·3	−11·3		−10·6
	0·1	F.H.T. (85°C quench)	None	+1·8		+3·8	−6·4		−7·0
	0·5	(cold forming)	,,	+6·8		+8·5	−10·3		−11·6
	1·0	,,	,,	+9·8		+12·4	−13·2		−13·4
	3·0	Annealed (cold forming)	F.H.T. (85°C quench)	−0·8		−1·7	−2·2		−2·4
	0·25	F.H.T. (85°C quench)	None	+3·2	+2·0	+2·9	−6·1	−5·2	−6·2
	0·5	(formed at 140°C)	,,	+6·9	+6·0	+5·5	−8·7	−9·8	−7·5
	1·0	,,	,,	+7·8	+9·1	+8·2	−12·1	−13·2	−12·2
	Zero	Solution treated (cold	None		−1·8		−1·8		
	0·2	quench), 1½ per cent	,,	+6·8		+9·2	−9·5		−11·2
	0·5	stretched. Artificially	,,	+11·7		+11·3	−14·7		−13·4
	1·0	aged. (Cold forming)	,,	+13·3		+11·9	−16·5		−15·1
DTD 687	Zero	2 hours after solution	Artificially aged		−1·9				
	0·73 (68*t*)	treatment (cold quench)	,,		+5·7			−7·2	
	4·7 (10*t*)	(cold forming)	,,				−5·5		−8·4
	7·7 (6*t*)	,,	,,					−5·7	
	16 (2½*t*)	,,	,,				−10·8		−5·4
	4·7 (10*t*)	6 hours after solution	Artificially aged				−7·5		−10·1
	7·7 (6*t*)	treatment (cold quench)	,,				−7·4		−7·6
	16 (2½*t*)	(cold forming)	,,				−5·2		−5·3
	0·53 (94*t*)	F.H.T. (cold quench)	None		+10·7			−12·4	
	0·6 (84*t*)	(cold forming)	,,				−14·5		−14·5
	2·6 (19*t*)	,,	,,					−14·3	
	4·75 (10*t*)	,,	,,				−9·8		−13·1
	5·9 (8*t*)	,,	,,				−12·0		−16·5
	6·65 (7*t*)	,,	,,				−15·0		−12·7
	7·7 (6*t*)	,,	,,				−13·0		−19·0
L 65	0·1	2 hours after solution	Artificially aged	+0·5		+2·3	−10·5		−10·1
	1·0	treatment (cold quench)	,,	+4·9		+4·3	−9·4		−9·2
	4·0	(cold forming)	,,	+4·7		+5·4	−11·1		−10·4
	10·0	,,	,,	+8·6		+9·0	−11·0		−10·1
	0·1	6 hours after solution	Artificially aged	−0·9		0	−8·4		−10·5
	1·0	treatment (cold quench)	,,	+3·9		+3·5	−9·3		−11·1
	4·0	(cold forming)	,,	+7·5		+2·7	−8·3		−9·0
	Zero	F.H.T. (cold quench)	None		−8·6		−9·1		
	0·1	(cold forming)	,,	+1·9		+4·4	−12·5		−12·8
	0·2	,,	,,	+3·1		+6·0	−13·4		−14·1
	0·5	,,	,,	+9·2		+6·1	−16·3		−16·1
	1·0	,,	,,	+10·1		+12·3	−14·8		−18·0
	Zero	Solution treated (cold	None		−2·4		−5·2		
	0·1	quench) 1½ per cent	,,	+0·5		+0·3	−6·9		−5·7
	0·2	stretched. Artificially	,,	+1·5		+3·1	−6·5		−8·4
	1·0	aged. (Cold forming)	,,	+4·6		+6·3	−10·4		−10·7

Bend radii in terms of sheet thickness are given in parentheses

properties at the time of forming and (*b*) to the stress relieving effect of artificial ageing. The time delay between control stretching (which is carried out immediately after solution treatment) and forming would be varied between one day and a few months. This programme is at present in hand at the Laboratories of The Fairey Aviation Company.

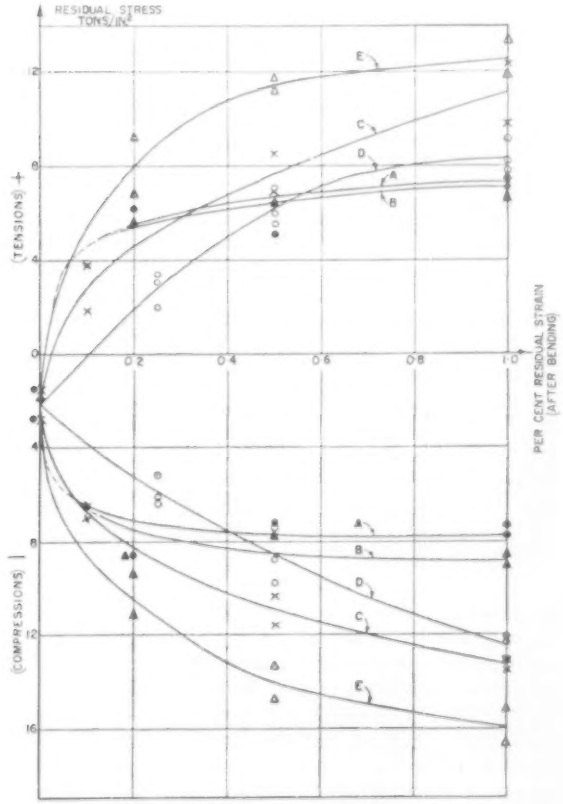
The time limit often imposed between solution treatment and forming when the latter operation is carried out in the solution treated condition appears to be rather unnecessary. The results have shown no significant change in residual stress when this limit has been increased from 2 to 6 hours. Further *ad hoc* investigations have confirmed this up to 48 hours and it has been shown that a delay of 10 months only results in stresses about 2 tons/in.^{2} higher at a 3 per cent residual strain than the same strain carried out within a few hours of solution treatment. The mechanical properties of the test bars which had naturally aged for 10 months and had then received a full artificial ageing treatment were determined and found to be well within specification requirements.

Evidence of practically complete removal of forming stresses by solution treatment has been given by forming a bar in the annealed condition and then fully heat treating it (solution treat and artificially age). The resulting stresses are those primarily due to quenching and although the stresses on the compression face are more positive (positive with respect to tension) than those on the tension face, there is very little difference in stress level between the two faces of the bar and an exposed tensile stress does not exist.

4.2. DTD 687 SHEET

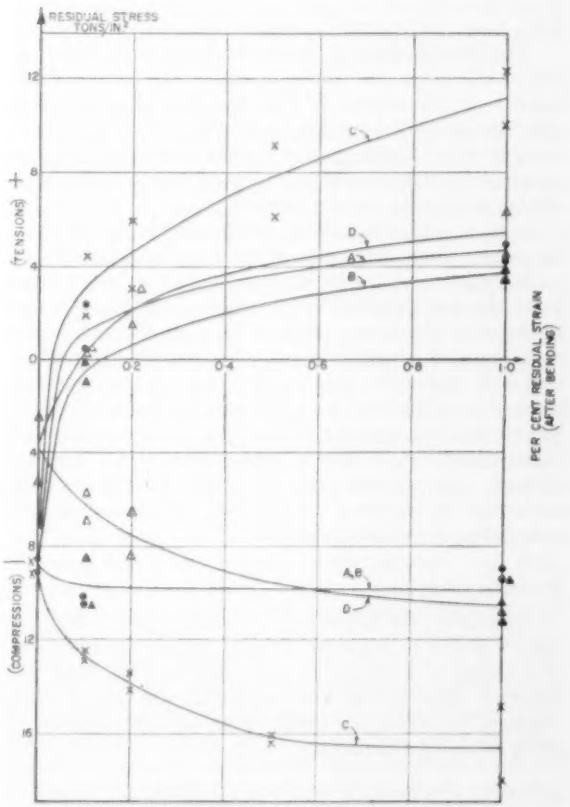
In the case of DTD 687 sheet material, the stresses resulting from forming have been measured only after forming in the solution treated condition and in the fully heat treated condition. No curve has been drawn through the residual stress/strain figures obtained since these do not seem to bear a convenient relationship to one another.

In the majority of practical applications the strain imposed upon DTD 687 sheet is considerably greater than that undertaken on DTD 683, but even when these



Curve: A. (●) Cold formed 2 hours after solution treatment.
B. (▲) Cold formed 6 hours after solution treatment.
C. (×) Cold formed after full heat treatment.
D. (○) Hot formed after full heat treatment.
E. (△) Controlled stretched, precipitated, cold formed.

FIGURE 1. The relationship between residual stress and residual strain, on bending extruded bars to DTD 683 specification under conditions of four point loading.



Curve: A. (●) Cold formed 2 hours after solution treatment.
B. (▲) Cold formed 6 hours after solution treatment.
C. (×) Cold formed after full heat treatment.
D. (△) Controlled stretched, precipitated, cold formed.

FIGURE 2. The relationship between residual stress and residual strain, on bending extruded bars on B.S.S. L65 specification under conditions of four point loading.

residual strains are reduced to below 1·0 per cent there does not seem to be any significant drop in stress.

When forming in the solution treated condition to any strain between 0·7 per cent and 16 per cent the residual stresses measured on the tension face lie anywhere between -5 and -10 tons/in.^{2} after artificial ageing. The residual tension, (in most of the aforementioned cases not measured) on the compression faces would be expected to be about 1 or 2 tons lower than the corresponding compressions measured on the tension face.

Similar conclusions may be drawn from the results obtained when forming the sheet in the fully heat treated condition. In this case the residual strain has been varied from 0·5 per cent up to 7·7 per cent and scattered stress values have been measured on the tension face between -10 and -19 tons/in.^{2}.

It should be noted, though this is of little practical significance, that the strains have been evaluated over the original sheet thickness (core plus cladding) whereas the stresses have been measured on the core material after removal of cladding. This in effect slightly lowers the residual strains reported.

4.3. B.S.S. L65 EXTRUDED BAR

The results derived from measurements made on L65 extruded bar are shown in Fig. 2. The most notable feature of the curves is the high compressive stress which exists in the surface layers (due to cold quenching) prior to bending; this results, after bending, in compressive stresses which are considerably higher than the corresponding tensile stresses.

It is noted, without any satisfactory explanation at the present time, that lower stresses result when forming is carried out 6 hours after solution treatment than when the same operation is completed within 2 hours of solution treatment (curves *A* and *B*). Also, the magnitude of residual stress, after forming controlled stretched and fully heat treated bar, is considerably lower than when forming unstretched, fully heat treated bar to the same residual strain; this reduction being far more significant, from the point of view of forming stresses, than in the case of DTD 683 where little advantage is obtained in forming the stretched bar rather than the unstretched bar.

5. Conclusions

The main conclusion to be drawn from this work, is that, where it is required to keep residual stresses due to forming to a minimum, it is necessary to form the material when it has low properties and also, where possible, to utilise the artificial ageing technique as a stress relieving treatment.

This precipitation treatment has been shown to relieve the magnitude of residual stresses by 25 to 40 per cent. By way of further example it can be shown that, for the same degree of forming: lower residual stresses result after forming L65 in the solution-treated condition and then artificially ageing, than by forming the lower strength L64 (naturally aged L65).

Finally, the following brief notes may be considered, where they are applicable to particular problems.

(*a*) Slight, controlled reverse bending will considerably reduce the level of surface residual stress and in some cases could be used to reverse the sign of the original stress distribution.

(*b*) If a sheet material is formed round a certain radius former, it will spring back to a larger radius on release of the bending moment. If now, this component is elastically deformed to a radius between these two radii, it is possible to virtually eliminate surface residual stresses, but internal stresses will be higher. This is due to the algebraic addition of a straight line elastic stress component through the sheet thickness onto the "as formed" stress pattern.

(*c*) In most cases exposed tensile stresses are undesirable, though unavoidably present. For low bending strains these tensile stresses can sometimes be avoided by forming cold water quenched, unstretched material with its high initial surface compression rather than stretched bar or hot water quenched material.

(*d*) Also, in the majority of cases, lower residual stresses are obtained when the material is deformed elastically for low strains, rather than given a permanent set. This would have most practical significance for sheet materials.

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A Theoretical Treatment of the Flutter of a Wing with a Localised Mass

by

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Flutter calculations were made on a fixed root model wing carrying a localised mass. Modes were calculated for the wing for certain conditions of restraint at the localised mass position, the choice of modes being based on observation of the behaviour of wind tunnel models under fluttering conditions. The general agreement between the calculations and experimental results was good and justified the extension of the calculations to conditions of localised mass loading that were not covered by experiment. The extended calculations show that there is an optimum spanwise position for a localised mass from the flutter point of view and, that this optimum position is related to the nodal line position in the overtone torsion mode of the bare wing. For values of localised mass parameters likely to occur in practice, flutter speeds can be estimated from calculations in a very limited number of modes, the choice of modes depending on the localised mass loading.

1. Introduction

Wind tunnel tests show that, so far as flutter is concerned, there is an optimum spanwise wing section for carrying a localised mass[1]. It has been suggested[2] that this optimum section is related to the position of the nodal line in the overtone torsion mode of the bare wing. If such a relationship exists, then the optimum section can be simply determined from mode calculations or resonance tests. There are, however, minimum inertia conditions of the localised mass that must be satisfied if the most favourable flutter characteristics are to be obtained, and the chordwise position of the mass is of primary importance. It is necessary, therefore, in any investigation into the optimum position for a localised mass, to examine all the mass parameters that could influence the flutter characteristics. This paper describes such an investigation and the results confirm that the optimum section is very close to the nodal line position in the overtone torsion mode of the bare wing.

The overtone modes used in the investigation were calculated for the wing with certain conditions of restraint at the localised mass section. It is shown that modes of this type have some advantages in localised mass investigations, and lead to a reduction in the number of degrees of freedom that need be considered.

2. Flutter Calculations

2.1. GENERAL

Wind tunnel experiments have shown[1] that an optimum section exists on a wing at which the attachment of a localised mass will result in a flutter speed that is higher than that obtained for any other spanwise mass position, provided certain conditions of mass value and chordwise position of the localised mass are observed. For the wing of Ref. 1 this optimum section was in the region of 0·75 span, but was not determined accurately. Although the calculations to be described here were primarily concerned with the optimum section, it was also decided to cover localised mass conditions that had already been covered by wind tunnel tests. Agreement between calculation and experiment would then justify the extension of the calculations to the investigation of optimum conditions. A subsidiary investigation could also be made of the effect of pitching radius of gyration of the localised mass—a parameter that has not been fully investigated in experiment.

2.2. WING AND MODES

It was originally intended that the wing details used in the calculations should be the same as those for a wind tunnel model with known flutter characteristics. The model chosen was one of a series used by Molyneux for fixed root flutter tests[3] and was an untapered wing with a uniform spar and constant spanwise mass distribution. As a result of preliminary calculations it was found that divergence of the wing occurred well within the flutter speed range that would be covered by the investigation, and to avoid this the flexural axis position used in the calculations was taken to be at 0·25 of the wing chord instead of 0·35 chord, as it actually was for the model. The inertia axis was also taken at 0·35 chord instead of 0·45 chord. Full details of the wing as used in the calculations are given in Table I and Fig. 1.

Observation of the flutter that occurred with a localised mass on a model wing showed that there were three main types[1]. Firstly a type that appeared to be a combination of the fundamental flexural and torsional modes of the wing; the amplitude of the localised mass was large. Secondly, with a localised mass at, or near, the tip, a type of flutter occurred for certain conditions of the localised mass in which the mass appeared to be on a nodal line; the oscillation combined motion in flexural and torsional overtone modes of the wing, the maximum amplitude occurring at about mid span. Thirdly with a localised mass at, or inboard of, half span the overtone form of flutter consisted of little or no movement of the localised mass and of the wing inboard of the localised mass. In general appearance the motion was similar to a fundamental type of flutter for the portion of the wing outboard of the localised mass.

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Molyneux[2] suggests that calculations using five specially chosen arbitrary modes will cover all the different types of flutter that may occur for the fixed root wing with a single localised mass. Modes of the type he suggests were used for the calculations, and they are: —

Mode 1. Fundamental flexure.
Mode 2. Fundamental torsion.
Mode 3. Flexure of the wing when restrained to prevent displacement at the localised mass section.
Mode 4. Torsion of the wing between the root and the localised mass section when restrained in twist at the localised mass section.
Mode 5. Torsion of the wing between the tip and the localised mass section when restrained in twist at the localised mass section.

The first two modes are invariant with localised mass position; the remainder depend on mass position, but in each mode the localised mass is at a nodal point. Uncoupled modes were calculated for the wing using the discrete mass method; for modes 3, 4 and 5 four spanwise positions of the localised mass were chosen, half, two-thirds, and three-quarter span and at the tip. The displacement curves for the modes are given in Figs. 2 and 3. Polynomials were fitted to the curves and are listed in Table II.

The frequencies chosen for the fundamental modes 1 and 2 were 3·6 and 14·5 cycles per second respectively, these being the values for the wind tunnel model of Ref. 3. The frequencies of the overtone modes were related to these frequencies and are given in Table III.

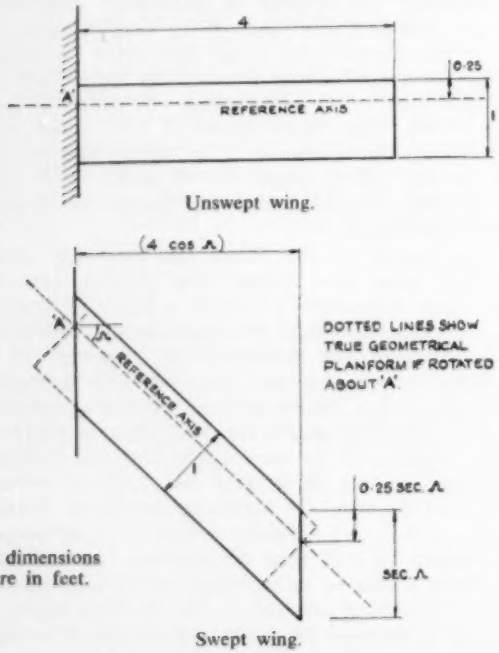

FIGURE 1. Details of wing geometry.

TABLE I
WING DETAILS (UNSWEPT)

Geometry

Span (root to tip) $s = 4$ ft.
Chord $c = 1$ ft.
Taper ratio (tip chord/root chord) = 1
Aspect ratio ($2s^2$/area) = 8

Inertia

Mass per unit span, $\overline{m} = 0{\cdot}0373$ slugs/ft.
Mass moment per unit span about reference axis,

$$\overline{mx} = 0{\cdot}00373 \text{ slugs ft./ft.}$$

Mass moment of inertia per unit span about reference axis,

$$\overline{mk}^2 = 0{\cdot}002002 \text{ slugs ft.}^2/\text{ft.}$$

Axes

Reference axis: 0·25c.
Flexural axis : 0·25c.
Inertia axis : 0·35c.

2.3. COEFFICIENTS IN THE FLUTTER EQUATIONS

The terms in the flutter equations were calculated in accordance with R.A.E. practice[4]. In the case of the inertia coefficients the localised mass affected only the direct and cross inertia terms in the fundamental modes 1 and 2. The localised mass was assumed to have zero moment of inertia in the roll sense. The direct stiffness terms were obtained from the direct inertia terms and the mode frequencies. The cross stiffness terms that existed between each of the flexure modes, and each of the torsion modes, were calculated using the modal functions of Table II. Two-dimensional incompressible flow derivatives were used in the aerodynamic terms[5], no correction being made for aspect ratio. A frequency parameter $\nu = 0{\cdot}6$ was assumed throughout. Aerodynamic effect of the localised mass was not allowed for. All the coupling terms between the overtone torsion modes 4 and 5 were zero.

2.4. SWEEPBACK

The effect of sweepback was investigated by considering rotation of the wing about the root in the manner shown in Fig. 1. The modes and mode frequencies remain unaltered with sweepback but, in the case of the flexure modes, wing sections in the line of flight are twisted by an amount proportional to the slope of the displacement curve for the mode. Thus, for a flexure mode whose displacement at a section distance y from the root is z, the twist of the section in the line of flight is given by: —

$$\theta = \frac{dz}{dy} \sin \Lambda$$

where Λ is the angle of sweepback of the wing. In practice there will also be a camber change across the section, but this is neglected in the calculations. As is shown in Fig. 1 the tip of the wing was assumed to remain parallel to the line of flight as the wing was swept-back. The aerodynamic derivatives were factored by $\cos \Lambda$.

2.5. SCOPE OF THE CALCULATIONS

The flutter equations were solved on the R.A.E. flutter simulator[6], and it was possible to investigate

TABLE II

MODE FUNCTIONS

The values of f and F denote, respectively, the displacement and twist of the flexural axis at a section η where ηs is the distance of the section from the wing root.

Mode 1. Fundamental flexure.

$f_1 = 1{\cdot}724822\eta^2 - 0{\cdot}729936\eta^3$

Mode 2. Fundamental torsion.

$$F_2 = \sin\frac{\eta\pi}{2}$$

Mode 3. Overtone flexure.

Localised mass at half span:

$f_3 = -2{\cdot}4889\eta^2 + 6{\cdot}6605\eta^3 - 3{\cdot}1718\eta^4$

Localised mass at two-thirds span:

$f_3 = -5{\cdot}8992\eta^2 + 13{\cdot}1434\eta^3 - 6{\cdot}2351\eta^4$

Localised mass at three-quarters span:

$f_3 = -10{\cdot}0375\eta^2 + 20{\cdot}412\eta^3 - 9{\cdot}5691\eta^4$

Localised mass at tip:

$f_3 = -11{\cdot}8464\eta^2 + 20{\cdot}1873\eta^3 - 8{\cdot}3521\eta^4$

Mode 4. Overtone torsion.

Localised mass at half span:

$F_4 = \sin 2\eta\pi$ for $\eta = 0$ to $\frac{1}{2}$

$= 0$ for $\eta = \frac{1}{2}$ to 1

Localised mass at two-thirds span:

$F_4 = \sin\frac{3\eta\pi}{2}$ for $\eta = 0$ to $\frac{2}{3}$

$= 0$ for $\eta = \frac{2}{3}$ to 1

Localised mass at three-quarters span:

$F_4 = \sin\frac{4\eta\pi}{3}$ for $\eta = 0$ to $\frac{3}{4}$

$= 0$ for $\eta = \frac{3}{4}$ to 1

Localised mass at tip:

$F_4 = \sin\eta\pi$

Mode 5. Overtone torsion.

Localised mass at half span:

$F_5 = 0$ for $\eta = 0$ to $\frac{1}{2}$

$= (\eta - \frac{1}{2})\pi$ for $\eta = \frac{1}{2}$ to 1

Localised mass at two-thirds span:

$F_5 = 0$ for $\eta = 0$ to $\frac{1}{3}$

$= \sin\frac{3}{2}(\eta - \frac{1}{3})\pi$ for $\eta = \frac{1}{3}$ to 1

Localised mass at three-quarters span:

$F_5 = 0$ for $\eta = 0$ to $\frac{1}{4}$

$= \sin 2(\eta - \frac{1}{4})\pi$ for $\eta = \frac{1}{4}$ to 1

Localised mass at tip:

$F_5 = 0$

a large number of localised mass conditions comparatively quickly, once the basic problem had been set up on the machine.

The calculations for the unswept wing were made for four spanwise positions for the localised mass, half, two-thirds, three-quarters span and the tip. Five modes were taken for the first three of these positions, but with the localised mass at the tip the overtone torsion mode 5 disappears (*see* Section 2.1). For each of these spanwise localised mass positions, the magnitude of the mass, its pitching radius of gyration and its chordwise position were varied. First a localised mass of magnitude 0·5 of the wing mass was traversed across the wing in a fore and aft direction. This traverse was made for two values of pitching radius of gyration of the localised mass (zero and 0·3 of the wing mean chord). Secondly, the effects of varying mass and radius of gyration were

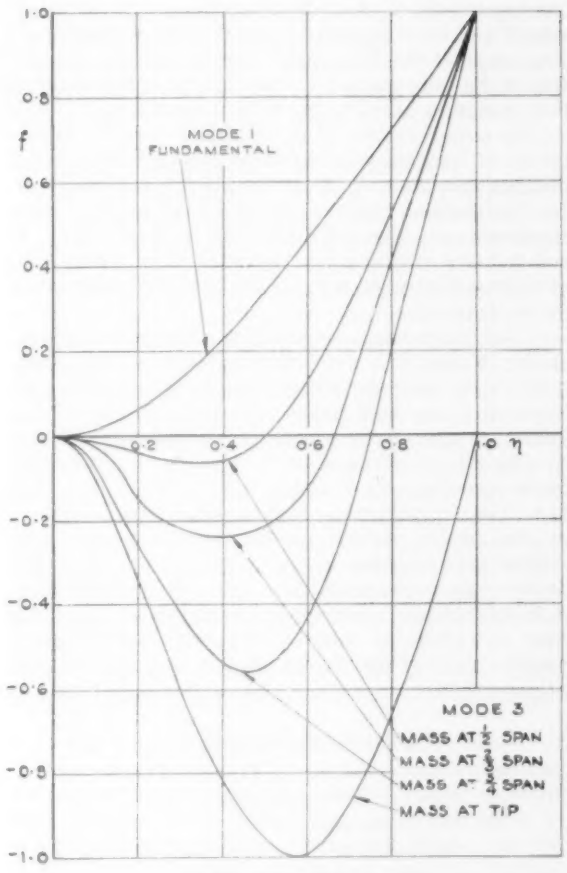

FIGURE 2. Flexure modes.

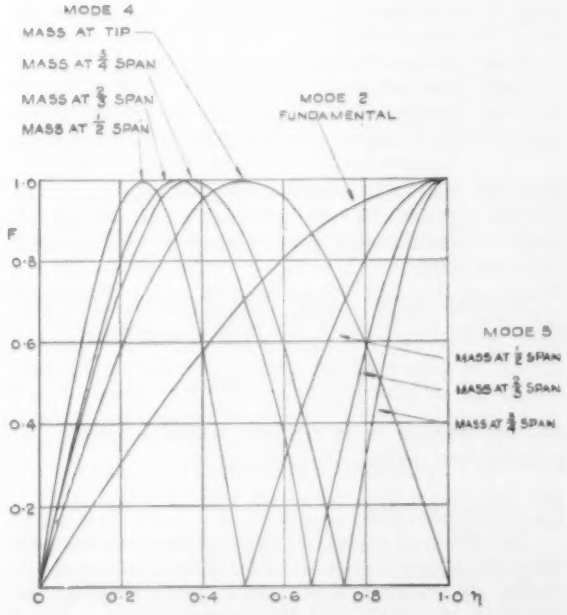

FIGURE 3. Torsion modes.

investigated for a chordwise position of the localised mass 0·1 of the wing chord forward of the flexural axis. The range of localised mass value was from zero to that of the wing mass, and the pitching radius of gyration from zero to 0·7 of the wing mean chord.

For each condition of the localised mass the flutter speed and frequency were obtained, both for the quinary problem (modes 1, 2, 3, 4, 5) and for the binary of the fundamental modes 1, 2. In addition, the flutter equations were solved for modes 3, 4, 5 and for 3, 4 and 4, 5 (*see* Section 4.4). The solutions of these were, of course, dependent only on the spanwise position of the localised mass.

Calculations were also made for angles of sweepback of 15°, 30° and 45°. Variations of localised mass parameter were made for the two-thirds span position of the mass at the three angles of sweepback, but for the remaining spanwise positions of the mass the flutter equations were solved for zero mass in the following mode combinations: 1, 2, 3, 4, 5; 1, 2; 3, 4, 5; 3, 4, and 3, 5. For the localised mass at two-thirds span, solution of the quinary problem on the flutter simulator was difficult for sweepback angles of 30° and 45°, since the nature of the modes resulted in ill-conditioned equations. A transformation[7] was applied to the flutter matrix in these two cases to eliminate the cross inertia terms between each of the flexure modes and each of the torsion modes.

3. Results of the Calculations

3.1. NOTATION

Λ the angle of sweepback

V the critical flutter speed

V_0 the flutter speed of the wing in modes 1, 2 at zero sweepback with zero localised mass

V_1 the flutter speed of the wing in modes 1, 2 at sweepback Λ with zero localised mass.

$\omega, \omega_0, \omega_1$ are the corresponding flutter frequencies for speeds V, V_0, V_1

m the mass value of the localised mass

m_w the mass of the bare wing

k the ratio of the localised mass pitching radius of gyration to the wing chord in the line of flight.

x the ratio of the distance of the centre of gravity of the localised mass aft of the flexural axis to the wing chord in the line of flight.

Although flutter speeds, frequencies and localised mass values are shown in the figures as ratios

$$\left(\frac{V}{V_0}, \frac{\omega}{\omega_0}, \frac{m}{m_w}, \text{etc.}\right)$$

they are referred to in the text as flutter speeds, frequencies, and masses, for convenience.

3.2. UNSWEPT WING

The effects of varying localised mass parameters are shown for masses at the tip and half span in Figs. 4—7. Similar results (not shown here) were obtained for masses at two-thirds and three-quarters span. These

TABLE III

MODE FREQUENCIES

Mode 1. Fundamental flexure	:	$\omega_F = 3{\cdot}6$ *c/s*
Mode 2. Fundamental torsion	:	$\omega_T = 14{\cdot}5$ *c/s*
Mode 3. Overtone flexure		
Localised mass at ½ span	:	$2{\cdot}90\,\omega_F = 10{\cdot}44$ *c/s*
Localised mass at ⅔ span	:	$5{\cdot}20\,\omega_F = 18{\cdot}72$ *c/s*
Localised mass at ¾ span	:	$6{\cdot}45\,\omega_F = 23{\cdot}22$ *c/s*
Localised mass at tip	:	$4{\cdot}34\,\omega_F = 15{\cdot}62$ *c/s*
Mode 4. Overtone torsion		
Localised mass at ½ span	:	$4\,\omega_T = 58{\cdot}0$ *c/s*
Localised mass at ⅔ span	:	$3\,\omega_T = 43{\cdot}5$ *c/s*
Localised mass at ¾ span	:	$8/3\,\omega_T = 38{\cdot}67$ *c/s*
Localised mass at tip	:	$2\,\omega_T = 29{\cdot}0$ *c/s*
Mode 5. Overtone torsion		
Localised mass at ½ span	:	$2\,\omega_T = 29{\cdot}0$ *c/s*
Localised mass at ⅔ span	:	$3\,\omega_T = 43{\cdot}5$ *c/s*
Localised mass at ¾ span	:	$4\,\omega_T = 58{\cdot}0$ *c/s*
Localised mass at tip	:	∞

results cannot be compared in detail with the results of experimental work because the wind tunnel tests of Ref. 1 did not cover the unswept wing case, and the calculations were not made for the wind tunnel model. There is, however, agreement on a qualitative basis for the variations that are common to both experiment and calculation. For instance, the occurrence of the fundamental and overtone types of flutter is a common feature of both investigations; also the variations of localised mass parameters produced similar effects on both flutter speed and type of flutter.

The present investigation covers a wider scope than the wind tunnel experiments in two respects, namely in variation of pitching radius of gyration of the localised mass, and in the investigation of the overtone forms of flutter. Considering first the variation of pitching radius of gyration, this is seen to affect both the fundamental and overtone forms of flutter and also the transition between them. Figs. 4 and 6 show that the addition of localised mass to the wing produces the fundamental form of flutter for mass values between zero and a critical value (which depends upon the position of the mass). The variation of the flutter speed in this fundamental form of flutter is influenced by the pitching radius of gyration of the mass. For zero value of k the flutter speed rises as mass is increased, but for relatively large values of k (0·7 of the wing mean chord) there is initially a reduction of flutter speed as mass is increased from zero, followed by a rise in speed with further increase of mass. The critical value of mass at which transition to an overtone form of flutter takes place is also slightly affected by the pitching radius of gyration of the mass. The critical mass value increases with increasing k. In the overtone forms of flutter that occur for localised mass values greater than the critical, the effect of pitching radius of gyration is pronounced. Figs. 4 and 6 show that two forms of overtone flutter may occur. For large values of the pitching radius of gyration ($k = 0{\cdot}5$ and $0{\cdot}7$) the overtone flutter speed is constant and the frequency is high. But for $k = 0$ and $0{\cdot}3$ the overtone flutter speed varies with mass, and the

frequency is lower than the overtone flutter frequency with large pitching radius of gyration of the mass. With the localised mass at the tip and a pitching radius of gyration of 0·3 (Fig. 4) both types of overtone flutter occur as mass is varied, and a clear distinction between them is obvious. It may also be noted from Figs. 4 and 6 that increase of pitching radius of gyration of the localised mass raises the flutter speed of the lower frequency overtone flutter until the higher frequency type becomes critical.

The investigation of the overtone forms of flutter consisted of the investigation already described in which overtone flutter ocurred for certain values of localised mass parameter (taking all five modes together), and a secondary investigation of the flutter speeds obtained from the ternary 3, 4, 5 and the binaries 3, 4 and 3, 5. The results are given in Fig. 10 in which the flutter speeds for the three mode combinations are plotted against spanwise position of the localised mass. To obtain a more detailed picture of the variation of flutter speed with span, the coefficients in the flutter equations for the four spanwise positions were interpolated graphically to obtain additional coefficients appropriate to 0·58, 0·65, 0·68, 0·80 and 0·90 span. Fig. 10 shows that a maximum value of flutter speed for modes 3, 4 and 5 occurs at about 0·7 span, and that the flutter speed is more than 2·5 times the bare wing flutter speed.

3.3. SWEPT-BACK WING

The range of localised mass parameter variation covered in the unswept case was repeated for the swept-back wing for a localised mass at two-thirds span. The results of these calculations for sweepback 30° are given in Figs. 8 and 9. The effect of sweepback agrees with the effect obtained experimentally[1] in that flutter speeds and frequencies increase, and the transition between fundamental and overtone forms of flutter for a given mass occurs at a more forward chordwise position as the sweepback is increased. (It may be noted that although the chordwise position of the localised mass is expressed as a fraction of the streamwise wing chord the latter increases with sweepback; the same applies to the value of the pitching radius of gyration of the localised mass which is also expressed as a fraction of streamwise wing chord.) The overtone flutter speeds have been obtained for modes 3, 4, 5 (also 3, 4 and 3, 5) for all four spanwise positions of the localised mass at three angles of sweepback 15°, 30° and 45°. These are shown plotted against span in Fig. 11.

4. Discussion of Results

4.1. COMPARISON WITH EXPERIMENT

It has already been stated that the calculations show broad agreement with experimental work. The occurrence of an additional type of overtone flutter with a localised mass at half span or at the tip (Section 3.1) is not inconsistent with the experiments of Ref. 1. The experiments were made, for the most part, with a localised mass pitching radius of gyration of 0·45 of the wing mean chord and the present calculations show that a smaller value of radius of gyration than this is required to make the new form of overtone flutter critical. For comparable values of the localised mass pitching radius of gyration, the calculations agree very well in all respects with the experiments of Ref. 1.

4.2. THE FUNDAMENTAL FORM OF FLUTTER

The fundamental type flutter is mainly dependent on the fundamental flexural and torsional modes 1 and 2. Flutter in these two modes alone can be eliminated by massbalancing the wing. The extent to which the overtone modes 3, 4 and 5 restrict the massbalancing effect can be seen in Figs. 4—9, where the flutter speed curves for modes 1 and 2 are shown alongside the equivalent curves for modes 1, 2, 3, 4, 5. In general, modes 1 and 2 give a fair approximation to modes 1, 2, 3, 4, 5 for the fundamental flutter branch of the curve, although there are conditions in which this is not the case. The largest discrepancy occurs with the localised mass at half span (Fig. 6). Lesser discrepancies occur with the mass at two-thirds span and with the wing swept-back (Figs. 8 and 9). Molyneux[2] and others have found that localised mass calculations using the fundamental modes alone agree closely with calculations that include overtone modes in the case of fundamental type flutter. The present work indicates that this is not always so, but there is more agreement when the localised mass pitching radius of gyration is small than when it is large.

4.3. THE OVERTONE FORMS OF FLUTTER

The overtone form of flutter mentioned in Sections 3.1 and 4.1 as occurring with a small value of localised mass pitching radius of gyration when the mass is at half span or at the tip is mainly a combination of modes 2 and 3—fundamental torsion and overtone flexure. Although a binary investigation of these two modes alone was not made it was noticed from the simulator that modes 1, 4 and 5 played little part in the motion. Since the occurrence of this type of flutter was restricted to localised mass positions at half span and at the tip, it may be assumed that the increase of stiffness in mode 3 as the point of restraint (*i.e.* the localised mass position) approaches the overtone flexure nodal line for the unrestrained wing, increases the flutter speed.

The overtone form of flutter which has occurred throughout the experimental work of Ref. 1 mainly involves modes 3, 4 and 5. In Figs. 4—9 the flutter speed in these modes alone is shown for comparison with the overtone flutter speed obtained by considering modes 1, 2, 3, 4, 5. The agreement is, in general, good and where the overtone flutter speed varies slightly with mass, as for instance, with a localised mass at the tip (Fig. 4 $k=0{\cdot}5$ and 0·7), the 3, 4, 5 solution for flutter speed is seen to be an asymptote to the quinary solution.

4.4. OPTIMUM LOCALISED MASS POSITION

In Sections 4.2 and 4.3 it has been stated that the fundamental flutter characteristics of the wing may be approximately obtained by consideration of the fundamental modes only, and the overtone characteristics by consideration of the overtone modes only. An exception is made for the form of overtone flutter that may

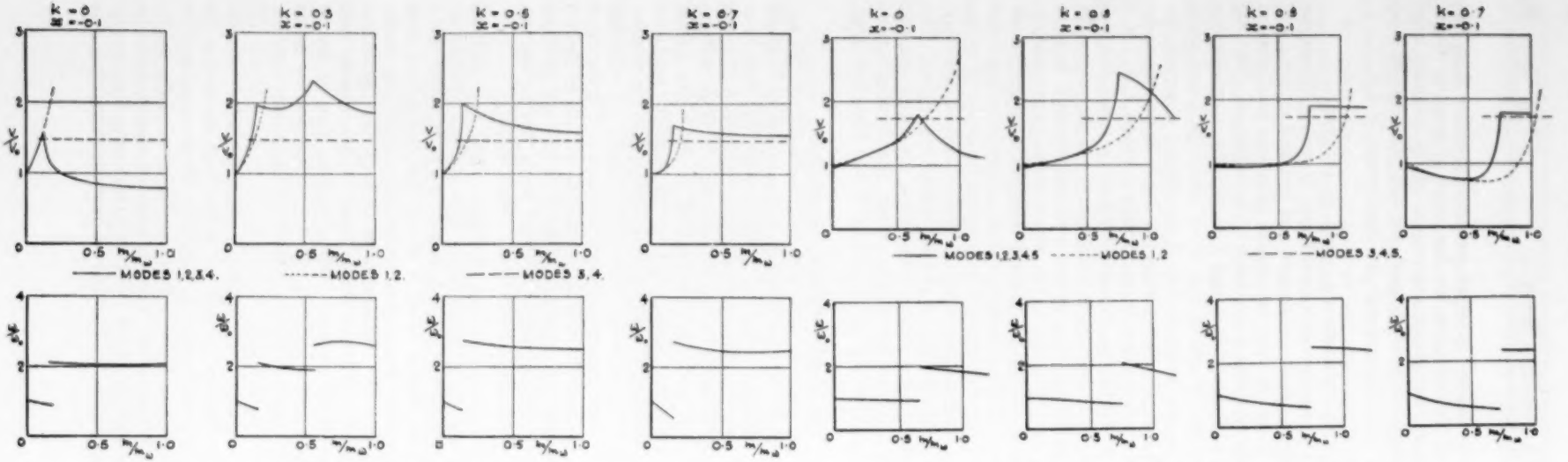

FIGURE 4. Localised mass at tip. $\Lambda = 0°$.

FIGURE 6. Localised mass at half span. $\Lambda = 0°$.

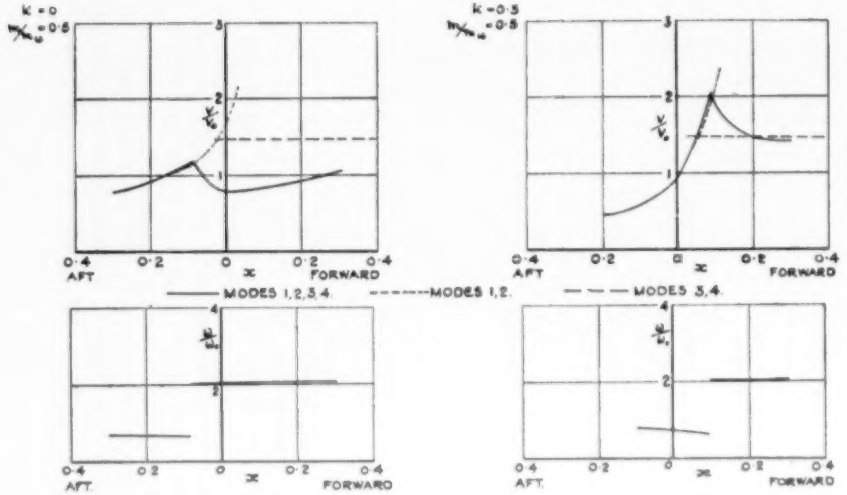

FIGURE 5. Localised mass at tip. $\Lambda = 0°$.

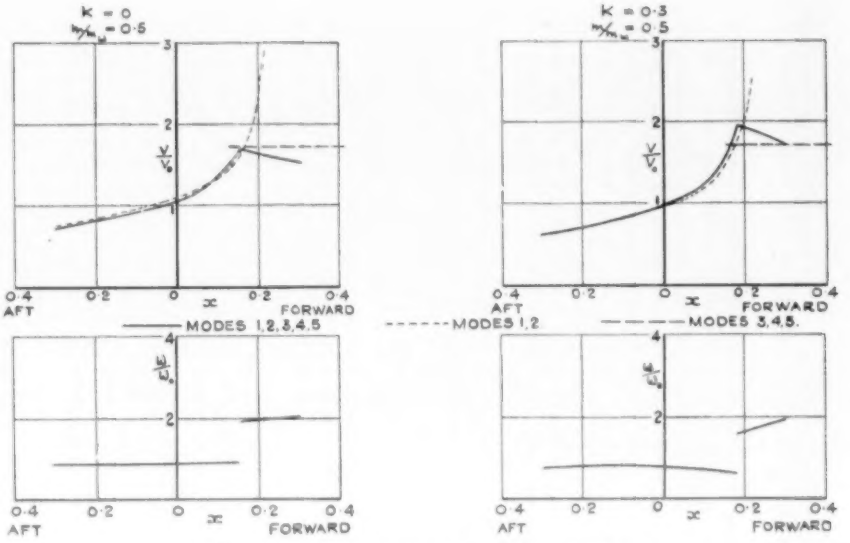

FIGURE 7. Localised mass at half span. $\Lambda = 0°$.

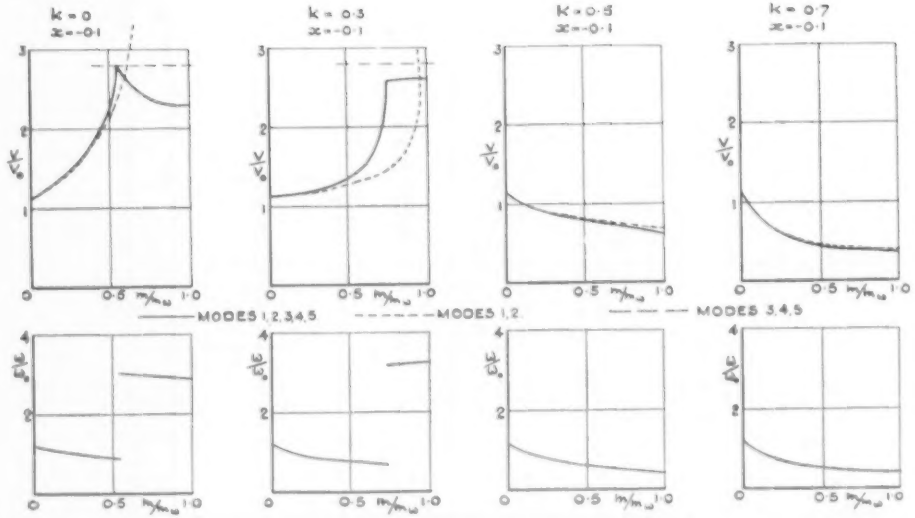

FIGURE 8. Localised mass at two-thirds span. $\Lambda = 30°$.

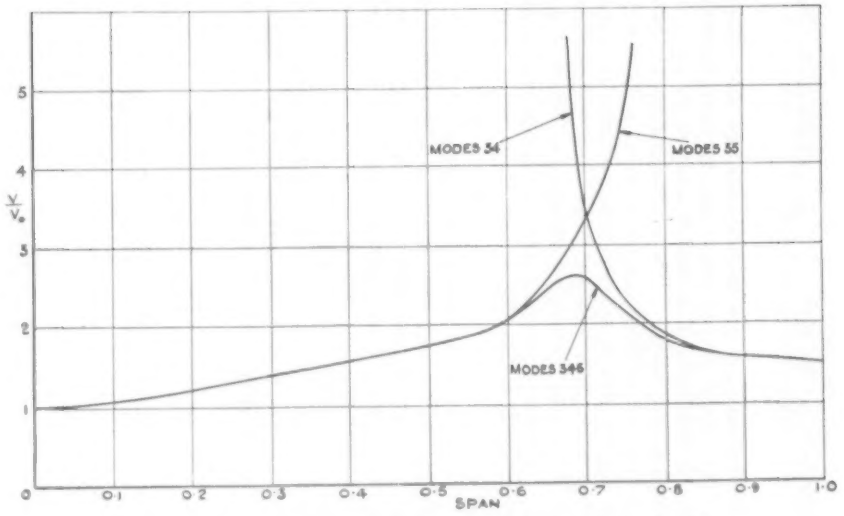

FIGURE 10. Variation of flutter speed for overtone modes. $\Lambda = 0°$.

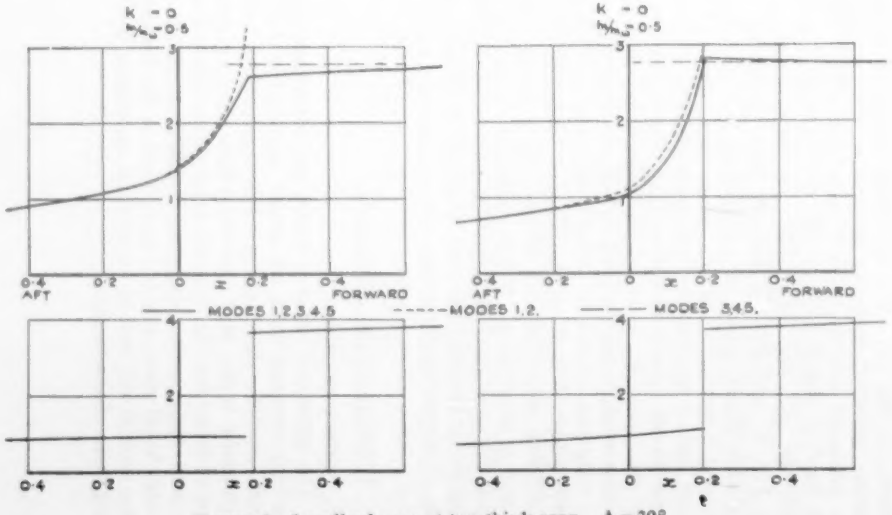

FIGURE 9. Localised mass at two-thirds span. $\Lambda = 30°$.

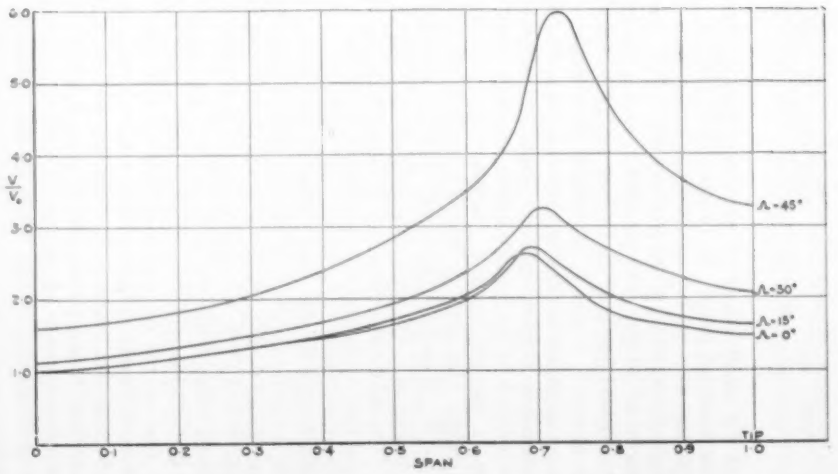

FIGURE 11. Variation of flutter speed for modes 3, 4, 5, plotted against span.

occur for small values of pitching radius of gyration of the localised mass. In practice however, this form of flutter will be of minor importance since it is associated with large masses having small pitching moments of inertia. For practical purposes the highest flutter speeds that may be attained are those associated with modes 3, 4 and 5, for which these modes alone give an asymptotic value of flutter speed. In Fig. 10 the variation of flutter speed in these modes with spanwise position of the localised mass is shown. With the mass at the root mode 3 becomes mode 1, mode 4 disappears, and mode 5 becomes mode 2, so that the ratio V/V_0 is unity. The speed rises to a maximum in the region of 0·68 span then falls away towards the tip. The maximum value is 2·6 times the flutter speed for the bare wing, and this represents the highest flutter speed that could be achieved by attaching a single localised mass to the wing. The importance of each mode in the flutter solution may be seen from the additional curves in Fig. 10 showing the flutter speeds for modes 3, 4 and 3, 5. For spanwise positions of the localised mass from the root to 0·6 span the binary 3, 4 gives the same flutter speed as the ternary. From 0·85 span to the tip the same applies to binary 3, 5. Between 0·6 and 0·85 span either binary gives a higher speed than the ternary (or alternatively is stable). Fig. 10 may be compared with Fig. 30 of Ref. 1, which shows the overtone speeds for a wind tunnel model.

Curves similar to Fig. 10 have been obtained for sweepback angles of 15°, 30° and 45° and these are shown in Fig. 11. The maximum occurs at slightly farther outboard spanwise sections as the sweepback is increased and is at 0·73 span for 45°. There is also a rapid increase in the maximum speed between 30° and 45°. Fig. 12 is a cross plot of Fig. 11 and from it may be seen the change in overtone flutter speed with sweepback for a localised mass at a particular section. Some wind tunnel results from Ref. 1 are included for comparison. Although these do not agree very well with the theoretical results for the asymptotic value of the flutter speed it should be remembered that the wind tunnel model differs from the wing considered here, in both plan form and stiffness distribution. It does appear, however, that the effect of sweepback shown by the calculations is greater than occurs in experiment. It will usually be of interest to know the overtone flutter speed in relation to the bare wing flutter speed at the same angle of sweepback, and Fig. 13 shows this variation.

5. Interpretation of Results

5.1. CHOICE OF MODES

The agreement between theory and experiment that has been obtained using the modes suggested by Molyneux[2] confirms their validity. His argument for using such modes is that since transitions from one to another type of flutter may be regarded as transitions from large to zero mass movement, then a judicious choice of modes based upon artificial constraints at the localised mass section will lead to an accurate assessment of the wing flutter characteristics.

In Section 4 it has been shown that the various branches of the flutter curve can be approximately obtained by selecting a limited number of the five modes for each branch. The approximations are best when the type of flutter is not close to a transition. This suggests that in many aircraft problems estimates of the effects of a localised mass could be obtained without the need for lengthy calculations. Even in the case of flutter conditions close to a transition the approximation is generally conservative.

5.2. OPTIMUM LOCALISED MASS SECTION

When the localised mass is at the section which is a nodal line for the overtone torsion mode of the bare wing, modes 4 and 5 have the same frequency and may be combined into the overtone torsion mode for the whole wing. The frequency is then greater than one of modes 4 and 5 for any other spanwise position of the localised mass. It is greater than mode 5, for example, for localised mass positions inboard of the overtone

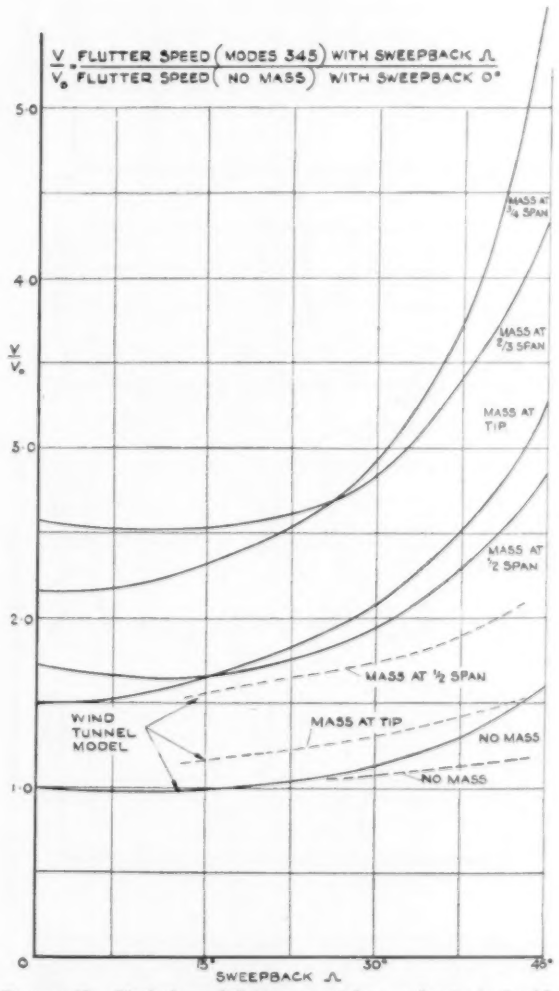

FIGURE 12. Variation of flutter speed for modes 3, 4, 5 with sweepback.

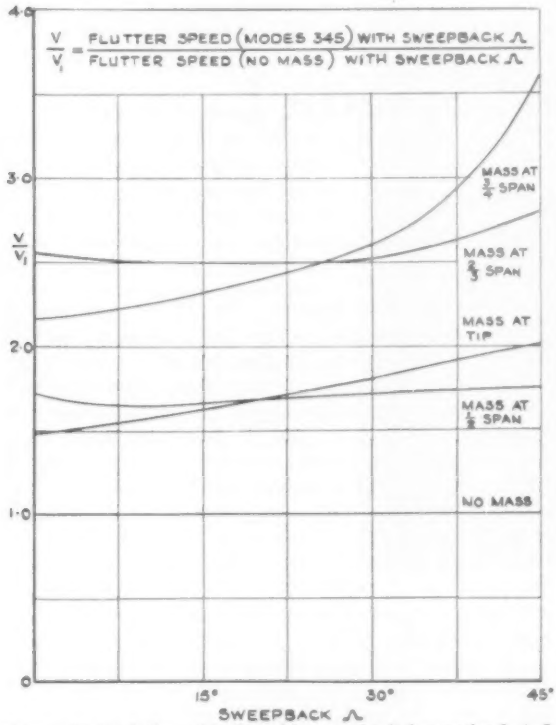

FIGURE 13. Variation of V/V_1 with sweepback for modes 3, 4, 5.

nodal line and greater than mode 4 for positions outboard. Following Molyneux's argument, the overtone flutter speed may be expected to depend on the lower of the frequencies of the torsion modes 4 and 5, and will therefore be a maximum when the mass is located at the nodal line of the overtone torsion mode of the bare wing. For a uniform wing, such as is considered here, the nodal line in the overtone torsion mode is at two-thirds span and it is clear that the occurrence of the maximum flutter speed in modes 3, 4, 5 is associated with this nodal line position. The maximum actually occurs slightly outboard of two-thirds span, but this is probably the effect of the overtone flexure mode 3 which is also varying with mass location. The optimum section also appears to move outboard as sweepback is increased, but the movement is not great and may be accounted for by the assumptions made in sweeping the wing back, and also by the inclination of the nodal line for overtone torsion to the line of flight when the wing is swept.

6. Conclusions

1. Flutter calculations on a fixed root wing carrying a localised mass, using modes based upon artificial restraints at the localised mass section, give flutter characteristics that agree well in general pattern with those obtained by experiment.

2. Comparison of the calculated flutter speeds with experiment shows that the theoretical treatment overemphasises the effect of sweepback.

3. The types of flutter that occur are each dependent on less degrees of freedom than were used in the calculations, and the flutter speed for a localised mass loading can be estimated by choosing degrees of freedom appropriate to the loading.

4. The optimum position for a localised mass is shown to be in the region of the nodal line for the overtone torsion mode of the bare wing. For a localised mass at this section satisfying the requirements for the avoidance of flutter involving the fundamental modes of the wing, the flutter speed is more than two-and-a-half times the bare wing flutter speed. This speed ratio increases with sweepback.

5. A subsidiary investigation of the effect of localised mass pitching radius of gyration indicates that the parameter can have an important effect on flutter in which the fundamental modes of the wing are involved. Within the range of values of the parameter likely to occur in practice the effect of variation is not great.

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The de Havilland Spectre I

by

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Introduction

Work on rocket propulsion was begun by the de Havilland Engine Co. in 1946, almost exactly a year after the end of the Second World War. For about the first year activities were confined largely to a general appreciation of rocket problems and techniques and to an assessment of the experience which had been obtained elsewhere. At that time "elsewhere" meant almost exclusively Germany, from where many technical reports were then becoming available.

In 1946 the policy in this country regarding guided weapons was, to say the least, obscure and the part which the liquid propellant rocket engine was to play in that field, even more obscure. It was not surprising, therefore, that the de Havilland Engine Co., being already well established in the field of aircraft propulsion, should very soon tend to concentrate its rocket propulsion efforts to manned aircraft applications. They were encouraged in this policy by the successful German use of the Me.163 and of rocket take-off units fitted to the He.111, Ju.88 and other aircraft. In particular, it was foreseen that the defence requirements of the United Kingdom might necessitate at an early date the use of a fast climbing rocket-propelled fighter.

In 1947 it was felt that the usefulness of the Comet I might be restricted by its marginal take-off capabilities from high altitude tropical aerodromes. Various schemes were considered to remove this restriction, one being the use of built-in rocket units and on the basis of this requirement the Sprite assisted take-off unit was designed.

In order to convince possible users of the practicability of rocket units for such a purpose and to obtain some first-hand experience of handling them and their propellants, two Walter 109-500 units were temporarily fitted to a Lancastrian aircraft. Altogether eight take-offs were carried out and no features were revealed which appeared to rule out the entire practicability of rocket units for civil aircraft.

Because of this satisfactory experience and for various other reasons, dealt with more adequately later, concentrated hydrogen peroxide or H.T.P. was chosen as the propellant for the Sprite. There was an especial reason for it being used for this application since it permitted so-called "cold" operation with no combustion. Such a simple system seemed highly desirable for a first venture in rocketry, particularly as this was intended for use on a civil aircraft.

The Sprite shown in Fig. 1 consisted primarily of a 40-gallon stainless steel H.T.P. tank feeding directly into a decomposer chamber. The H.T.P. was decomposed into steam and oxygen by a catalyst, calcium permanganate, fed into the chamber from a tank wrapped round its nozzle, both tanks being pressurised with air contained in cylinders disposed around the chamber. The unit was rated at 5,000 lb. maximum thrust for a duration of about 12 secs., and it was first fired early in 1950. Most of the problems with this unit were concerned with the air valves and more especially with the reducing valve, but by mid-1951 these difficulties had been sufficiently overcome to permit take-off tests in the Comet to be carried out. By that time, about 200 test bed firings had been accomplished including a flight approval special category test of 20 firings.

Altogether 27 Comet take-offs were made and on no occasion did the rocket units give any trouble worth recording. The trials were spread over about 15 months and during this period the Sprite was redesigned to use a solid silver catalyst instead of liquid calcium permanganate. This change greatly facilitated the refuelling procedure, eliminated the dirty brown exhaust of the liquid catalyst and provided valuable experience of solid catalysts which were subsequently used on the Spectre.

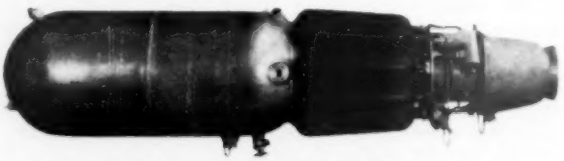

FIGURE 1. External view of Sprite.

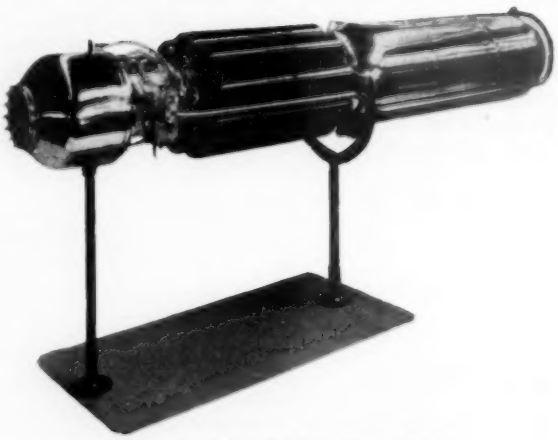

FIGURE 2. External view of Super-Sprite.

A Lecture given to the Society on 4th November 1958.

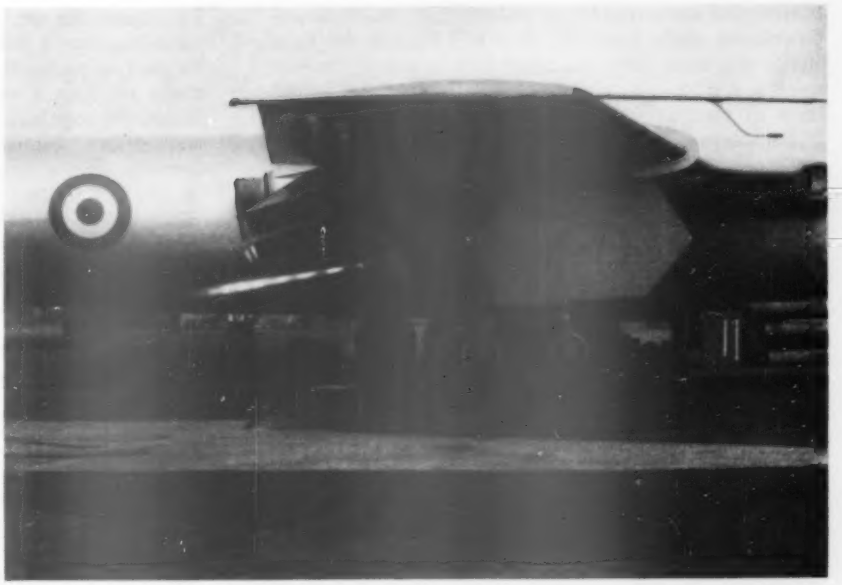

FIGURE 3. View of Super-Sprite nacelle on Valiant.

Although the feasibility of the Sprite was adequately proved, the units were never required operationally, since the take-off capabilities of later Comet variants were improved by the use of more powerful main engines. The capital cost of using rocket assistance for the Comet I only was clearly unjustified and the development of the Sprite proceeded no further than initial flight tests.

Two of the Sprite units thus made redundant were, however, modified to permit the combustion of fuel with the decomposed peroxide, and these units led logically to the Super-Sprite which is at present in quantity production for assisted take-off on the Valiant. The Super-Sprite is shown in Fig. 2 which indicates not only a family likeness to the Sprite but also the differences between the two units. These included an increase in H.T.P. and pressurising gas capacity by about 50 per cent and the replacement of the liquid catalyst tank of the original Sprite by a similar tank containing kerosine. This was used to cool the final convergent/divergent nozzle. The combustion chamber itself was still uncooled but was fitted with a flame tube which permitted the use of a combustion temperature of about 1,600°C with a corresponding performance increase compared with the Sprite. The Super-Sprite is rated at 4,000 lb. maximum thrust and a duration of about 35 seconds, this rating being fixed by aircraft requirements. Over 2,500 test bed firings and 60 take-offs have now been carried out with these units. On the Valiant, the Super-Sprite is contained in an external nacelle, one under each wing, situated between the main engine tail pipes as shown in Fig. 3. The nacelles are jettisoned after use and are brought down by parachutes. Landing shock is minimised by the use of air bags which are extended and inflated during the descent. Each nacelle with its engine can then be recovered and, after a small amount of reconditioning, subjected to repeated use.

All this is by way of introduction. It is, however, relevant since a great deal learned on the Sprite and Super-Sprite considerably influenced the design of the more advanced engine. For example, satisfactory experience on the earlier units helped to decide the propellants chosen for the Spectre. Both the Sprite and the Super-Sprite provided invaluable experience on material compatibility and the development of suitable solid catalysts. Both units provided prior knowledge of test bed design and testing techniques and in the case of the Super-Sprite, information on the combustion of kerosine in decomposed peroxide and the establishment of ignition limits, and so on.

Design Considerations

Even before work was begun on the Sprite and certainly concurrently with its development, thought was given to the use of a rocket engine to give super performance to a manned fighter. Ten years ago, it seemed that until the guided ground-to-air missile had attained sufficient reliability there might be a period during which a manned rocket fighter (if its development was begun soon enough) would be particularly suitable for the defence of the United Kingdom. Studies carried out indicated, as expected, the attractiveness of the rocket fighter with its high rate of climb, especially to high altitudes. These studies were extended to show, again as one would expect, how the range and duration limitations of the purely rocket-propelled fighter could be largely overcome by the use of both rocket and gas turbine power plants in the same aircraft. Similar studies were simultaneously carried out by Saunders-Roe, later to be elaborated and extended to form the integrated weapon philosophy of the S.R.177.

Design studies were therefore begun on a suitable rocket for a manned fighter. The over-riding principle for such an engine was that it should conform as nearly as possible to accepted proved aircraft engine standards. Above all, it should be robust and reliable, even if that meant, to begin with at any rate, some resulting weight penalty. It should be completely self-contained and capable of repeated operation during a flight and have a developed overhaul life equivalent, in number of sorties, to a gas turbine engine. It should be controllable over a wide thrust range, capable of straightforward installation, and demanding the minimum of attention between flights. Such then were the broad design requirements for the Spectre as originally conceived in 1947.

The first major decision to be made was that concerning the choice of propellants. A great number of

possibilities were considered, including the use of mono-propellants more powerful than H.T.P., but the final choice was soon narrowed down to kerosine as the fuel since it was readily available, and in any case would have to be supplied to a mixed engine aircraft, and liquid oxygen, nitric acid, or H.T.P. as the oxidant.

It was considered that the high evaporative rate of liquid oxygen rendered it unsuitable for use in an aircraft which needed to be at instant readiness. The possibility of using nitric acid was considered at much greater length, even to the extent of carrying out small scale ignition experiments with it and kerosine. Although highly corrosive and toxic, nitric acid was cheap and in plentiful supply and quite a lot was known about its storage and handling.

After consideration, however, H.T.P. was chosen, the reasons dictating the choice being mainly as follows. H.T.P. is about as non-corrosive as water, it is non-toxic, has a relatively high density and specific heat and a low vapour pressure. Experience with the Sprite and Super-Sprite had confirmed that it could be stored and handled safely and conveniently. When handled carelessly it could start a fire but in such a situation a supply of water would provide an immediate antidote.

As far as its use in a rocket engine was concerned, H.T.P. gives a good specific thrust and can be used for cooling the combustion chamber. The fact that it can be decomposed into steam and oxygen at about 600°C provides a ready means of ignition without the use of a spark plug and its associated electrical equipment and also a most convenient means of driving a turbine. Its stoichiometric combustion temperature is acceptably low and since the specific thrust/mixture ratio curve is fairly flat a simple valve system can be used since the exact mixture ratio at which the engine runs is not very critical. On the other hand it has certain disadvantages. For example, it has a relatively high freezing point and the materials for use with it need careful selection. Compared with nitric acid and liquid oxygen it was expensive and in fairly short supply, although it was felt that an increased demand for H.T.P. would soon create its own supply and that in turn this would result in a cost reduction. History has shown this to be true, and it is fair to say that subsequent experience has completely justified the choice of H.T.P. as the oxidant for the Spectre in particular and for aircraft use in general.

With regard to the size to which the engine should be designed, a survey was carried out through the Aircraft Industry and the recommendations obtained varied over a wide range from 2,000 lb. sea level thrust to 15,000 lb. Estimates at the lower end of the scale generally implied the use of a rocket in an adaptation of an existing aircraft or in a new aircraft designed to conventional standards, while the higher values usually coincided with the idea of a pure rocket interceptor with a very high climb rate and ultimate speed but with a very short endurance.

As a result of this survey and our own thoughts on the matter it was decided to design for a sea level thrust of 8,000 lb. with a possible later uprating of the engine to 10,000 lb. The amount of throttling required depended to a large extent on its application; it seemed that an engine for an all-rocket aircraft would require throttling over a wider range than if the rocket were to be used in partnership with a gas turbine. In order to cover all cases it was decided that initially the Spectre should be capable of throttling down to about 20 per cent of its full thrust rating but with development to a lower limit at a later stage.

Having decided the most suitable propellants and thrust rating, a decision was then made as to whether the necessary thrust variation could be obtained with a single combustion chamber or whether multiple chambers, each operating over a more restricted thrust range, would be required. Propellant consumption at part performance would certainly be better with multiple chambers (though negligibly so at great altitudes) but design layouts showing the nest of pipes and complicated control system resulting from such an arrangement convinced us that a single chamber capable of operating over the complete range would be simpler, lighter, more compact and reliable. We were encouraged by the thrust control achieved on the Walter 109-509 engine, our only reservation being the ability to cool with H.T.P. over the lower part of the range. With an insurance policy in mind, which will be mentioned later, we therefore embarked on a single chamber scheme.

The question then arose as to whether this should be fed by a conventional, separate, turbo-pump arrangement or whether we should use the quite radical low loss or "topping" turbine scheme in which the turbine exhausts into the combustion chamber. This latter scheme had the potential advantage of a higher overall specific thrust since the turbine exhaust was not ejected overboard with little or no propulsive effect. It also led to a compact arrangement of engine without a separate turbine exhaust and with a solid backbone on which control valves and gear could be conveniently hung with the minimum of framework. Fundamentally it led to an essentially safe ignition system since a steam flow from the turbine would constantly purge the combustion chamber of any fuel that might be left there unburnt. On the other hand, it would result in a rather inflexible arrangement since the turbine and pumps could not be easily removed from the head of the combustion chamber and disposed elsewhere. Furthermore, the turbine must inevitably work at a high pressure greater than that in the combustion chamber and this would necessitate a difficult seal adjacent to the turbine disc to prevent high pressure gas leaking down the pump drive shaft.

On balance it was felt that the advantages of the low loss system more than outweighed its disadvantages and the design of the Spectre proceeded therefore on these lines. If for no other reason, this decision has been subsequently justified on the grounds of safety, since the low loss system is inherently foolproof from the point of view of ignition. It is unlikely that fuel can be injected into the combustion chamber unless the turbine is running and there then must be a steam flow into the chamber. Consequently the fuel injected must either ignite or be swept away unlit and an explosive or hard start due to an accumulation of fuel in the chamber is therefore very remote.

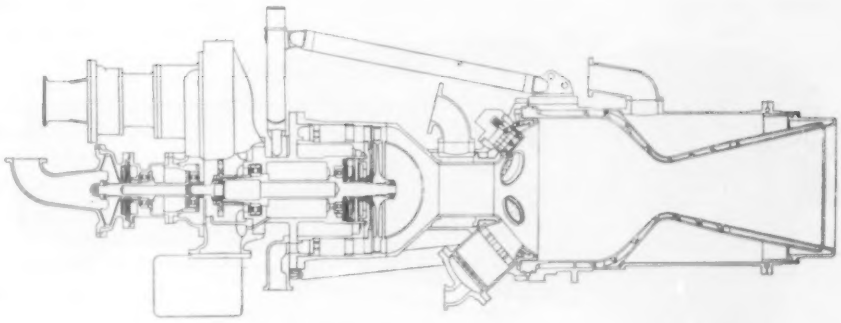

FIGURE 4. Sectional diagram of Spectre I as it first ran.

Our doubts about the use of H.T.P. as a coolant especially at low thrusts have been mentioned. In case these fears were justified, an alternative scheme was laid out in which the combustion chamber was cooled with water which was then passed through a heat exchanger, in which this heat was transferred to the H.T.P. about to be burnt in the engine. The water, having been cooled in this way, then passed round the combustion chamber again on a recirculatory system. Although the final temperature rise of the H.T.P. was exactly the same theoretically as it would have been if it were used to cool the chamber directly, it did not come into contact with the very hot combustion chamber wall, but only into contact with a very much cooler heat exchanger. It was thus felt that any local overheating and consequent decomposition of the H.T.P. would be avoided. Such a system was designed, made and run, but since very little trouble was experienced with direct H.T.P. cooling its development was very soon discontinued.

At one stage in its design the combustion chamber was cooled with high pressure H.T.P. delivered from a single pump, running at turbine speed. The combustion chamber was anchored at its forward end and in order to allow for thermal expansion the rear end was free to slide in the surrounding coolant jacket. With the coolant pressure higher than the combustion pressure this arrangement imposed an excessive combined buckling and tension load on the nozzle throat section. To overcome this the engine was re-schemed so that the H.T.P. was pumped up to pressure in two stages, passing through the coolant jacket at a relatively low pressure before passing into the second stage pump. This resulted in very low combustion chamber wall stresses but, of course, complicated the design of the gear box interposed between the turbine and the pumps.

A contract for the Spectre was received from the Ministry of Supply in mid-1951, although a great deal of preliminary work had been carried out before this. The rig testing of long life catalyst elements began early in 1952 and of mechanical components about three months later, but in order to make an account of this phase of the work more intelligible it is advisable to depart from a chronological sequence and before dealing with rig testing describe the engine as it first ran as a complete unit.

Figure 4 shows this in diagrammatic form. A stainless steel chamber was used, located as already stated, at its forward end. To permit easy inspection and replacement, the chamber was quite separate from the light alloy coolant jacket into which it fitted. Helical vanes were machined on the outer wall of the chamber to direct the H.T.P. flow and a two-piece filler block was clamped over the vanes to form rectangular coolant passages. The H.T.P. flowed forward over the chamber and was taken out at a point just aft of the turbine. Fuel was injected through three banks of injectors arranged at 120° to each other. Each bank contained fifteen swirl nozzles, and by a suitable valve it was arranged that these would be brought into action progressively as thrust was increased. At full thrust about half the total H.T.P. flow was fed directly into the combustion chamber through three cylindrical silver catalyst decomposers interposed between the banks of injectors. The remainder of the H.T.P. was fed through the turbine which was of a single stage impulse type running at a maximum speed of 13,000 r.p.m. This was fed from an annular decomposer through a simple nozzle ring giving partial admission. From the turbine, a shaft passed through the annular catalyst pack to a gear box on the front face of which were mounted the kerosine pump and the first and second stage peroxide pumps, running at 20,000, 7,500 and 13,000 r.p.m. respectively. The main drive, the gear box and the pump shafts were all run on conventional ball and roller bearings, lubricated from an oil sump at the base of the gear box. Forward of the turbine was a complicated gland which will be discussed in greater detail later. The pumps were of a very simple open impeller type with twin tangential diffusers, and an arrangement of multiple seals to prevent kerosine or H.T.P. leaking into the gear box. Also mounted on the front face of the gear box was a centrifugal flyweight governor similar to a propeller constant speed unit. Fig. 5 shows a side view of the engine.

The engine was controlled by a single throttle lever which varied the governor datum setting. This passed oil into or away from a servo piston which in turn varied the flow of H.T.P. to the turbine decomposer and hence the turbine speed. Linked with the governor control was a fuel control valve which staged the flow of fuel into the banked injectors, the ports on the control valve being designed to maintain a more or less constant overall mixture ratio over the whole thrust range.

The governor was intended to maintain a required turbine speed even in extreme conditions such as if the fuel ran out and a sudden loss of chamber pressure and hence turbine back pressure occurred. As an added precaution an overspeed valve was fitted, this being designed to shut down the flow of H.T.P. to the turbine on the advice of an excess pressure signal either from

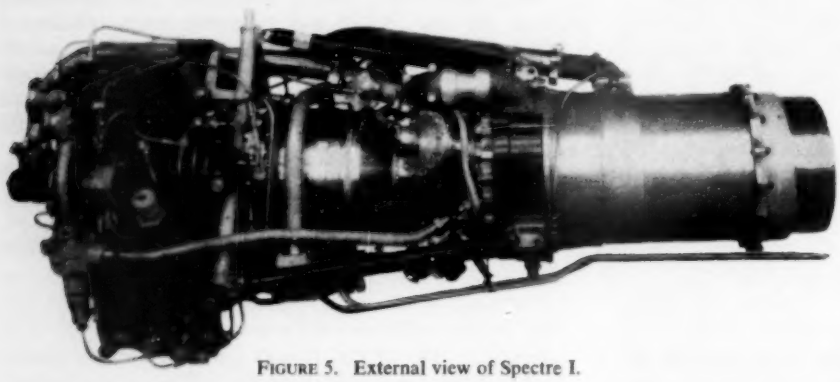

FIGURE 5. External view of Spectre I.

the coolant jacket or from the second stage H.T.P. pump.

Rig Testing

Before any engine running was attempted a great deal of testing was carried out on the valves, pumps, governor, turbine seal and starting system. The valves and pumps were tested with water on a special rig powered by a 160 h.p. variable speed electric motor and equipped with the necessary flowmeters and pressure gauges. Valves were tested for their correct operating pressures and pressure drops, and as many cycles as possible were carried out on each component. The pumps were endurance run and calibrated, pressure rise against flow and r.p.m. curves being produced and both inlet and diffuser cavitation limits obtained. The physical characteristics of water and H.T.P. are sufficiently similar to justify all this water testing being carried out. All the pump running was carried out using the actual Spectre gear box so that a great deal of running experience was obtained with this component at the same time. In fact the Spectre gear box/pump system became so reliable, that it was invariably used instead of the slave pump built into the rig when tests on valves were being carried out. A great deal of attention was paid to the sealing arrangements built in behind each pump impeller. These incorporated dynamic and static seals and although apparently a satisfactory standard was obtained by rig testing, subsequent test bed experience revealed some redesign to be necessary. This will be referred to later. The governor was mechanically and hydraulically tested and a great deal of work was carried out, modifying spring rates, and valve overlaps, and so on.

The turbine seal was exhaustively tested and a special rig designed to simulate engine conditions as closely as possible. In this rig the turbine shaft was driven by an electric motor and "steam" at its right pressure and temperature fed on to the seal from a small H.T.P. decomposer. To begin with, attempts were made to obtain a completely positive seal. The basis of each attempt was a system of carbon running rings either mounted on diaphragms or spring loaded carriers. No entirely successful arrangement was achieved and a combined labyrinth/carbon seal arrangement as shown in Fig. 6 was finally developed. In this design, the high steam pressure behind the turbine disc was reduced by stages through labyrinths, the spaces behind these being vented to atmosphere, the total overboard flow of steam being acceptably small. A positive seal was then made against a very low pressure by means of a bellows-mounted carbon ring rubbing against a shoulder on the shaft, the carbon ring being cooled by oil circulated from the gear box. Tests showed that it was impossible to ignite this oil with the adjacent low pressure steam, a number of runs being carried out with the carbon seal intentionally defaced to permit leakage. Considerable work went into obtaining the correct fit for the labyrinths, the stiffness of the bellows and the grade of the carbon, but eventually some hundreds of hours of successful rig running were carried out before any tests on the engine itself.

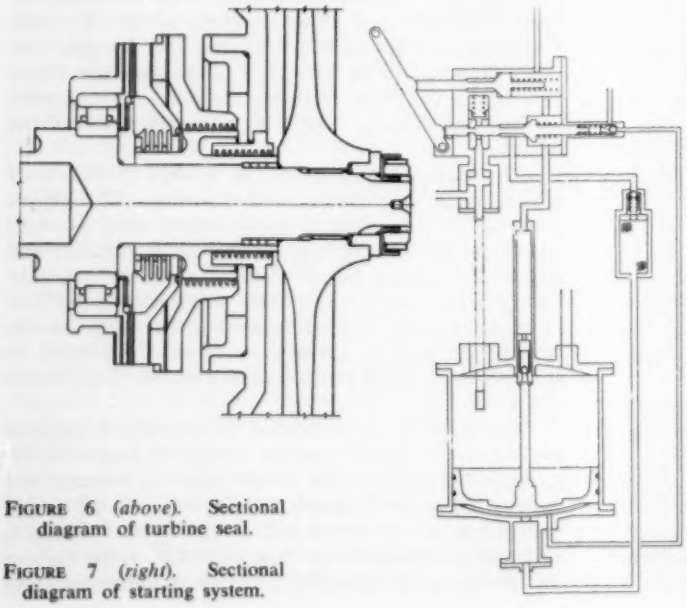

FIGURE 6 (*above*). Sectional diagram of turbine seal.

FIGURE 7 (*right*). Sectional diagram of starting system.

Another engine component amenable to separate testing was the starting system. This is shown in Fig. 7 and consisted essentially of a cylindrical tank containing about a gallon of H.T.P. which was automatically filled when the engine was prepared for a run. At the top of this tank there was a small plunger pump which when operated forced a small quantity of H.T.P. into a decomposer at the bottom of the tank. The steam so formed forced up the

piston in the tank, ejecting its contents into the turbine decomposer. The turbine then starts and the engine becomes self-motoring, and by means of a simple valve system the starting tank was then filled up for another start. The problems associated with this arrangement were mainly mechanical, generally concerning friction between moving parts such as the piston in its tank. To overcome this the tank was lined with a thin film of PTFE.

Bench Testing

Although the use of a low loss turbine system produced an integral arrangement of engine, the Spectre was surprisingly amenable to step by step testing. It has already been explained how the pumps, valves, turbine seal and starting system were individually rig tested. The next stage was to take the turbine decomposer without the turbine or gear box and to run it on H.T.P. from pressurised tanks, in order to check the distribution of peroxide into the decomposer and its decomposition efficiency. After this phase had been satisfactorily completed, the turbine, gear box and pumps were fitted and the turbine was run again from pressurised tanks with the H.T.P. pumps running on water, and the fuel pumps on kerosine. To simulate different chamber conditions, throttle plates were bolted to the casing downstream of the turbine to give it varying back pressures.

After this had been done the turbine was then run from the engine's own pumps, and soon afterwards the combustion chamber was fitted and the main decomposers brought into action. For this test the combustion chamber was cooled with water from a slave test bed system, the first cold run of this nature being carried out by mid 1953. The first hot run was carried out in the autumn of 1953, the combustion temperature being initially kept down to about 1,700°C by the use of a 16:1 mixture ratio. Stoichiometric and full thrust conditions were achieved about 6 months later and "hot" running with H.T.P. cooling about 6 months after that. Very soon considerable running between thrusts of 1,000 lb. and 9,000 lb. was carried out and no really serious fundamental difficulties with H.T.P. cooling were encountered anywhere in this thrust range.

No attempt will be made to describe all the many changes which were made between first running the engine and carrying out a flight approval test. Fig. 8 shows how running time was accumulated during this period. In parallel with complete engine running and component testing, a great amount of work was carried out both in the laboratory and by means of rig testing to improve the performance and reliability

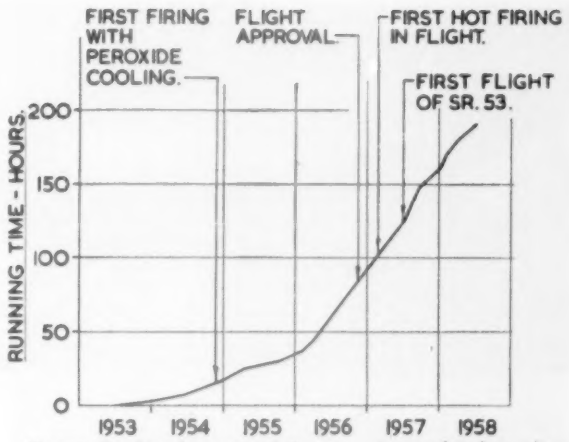

FIGURE 8. Development of Spectre. Accumulated running time.

of catalyst elements, to obtain better materials, both from the compatibility and corrosion aspects and to overcome the many sealing problems which arose. Concurrent with engine running, the test facilities themselves needed considerable development and methods of instrumentation were revised and improved.

Flight approval for the engine was obtained in the autumn of 1956 and a fair indication of the amount of development which had been carried out since the engine first ran will be apparent from an examination of Fig. 9 showing the engine as it was flight approved.

To begin with, the governor had been completely eliminated. This had been included in the original design because it was then not known whether a system involving a low loss turbine, centrifugal pumps and catalyst packs, would have sufficient inherent stability. The governor had however always been an inconsistent performer and tests showed that a system in which the H.T.P. was metered to the turbine by means of a valve directly linked to the throttle was quite practicable. Any tendency to overspeed would be looked after by the pressure operated overspeed valve which had always been a part of the propellant system.

It was found unnecessary to stage the fuel injectors in order to obtain low thrust performance. This was rather fortunate because frequent blow backs in the injectors had necessitated non-return valves right at

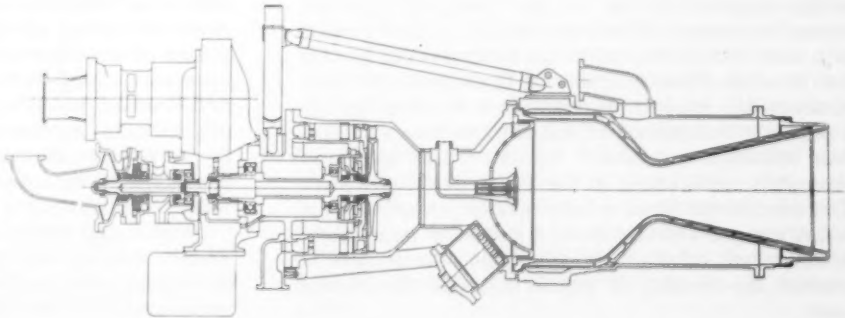

FIGURE 9. Sectional diagram of Spectre I as it was cleared for flight.

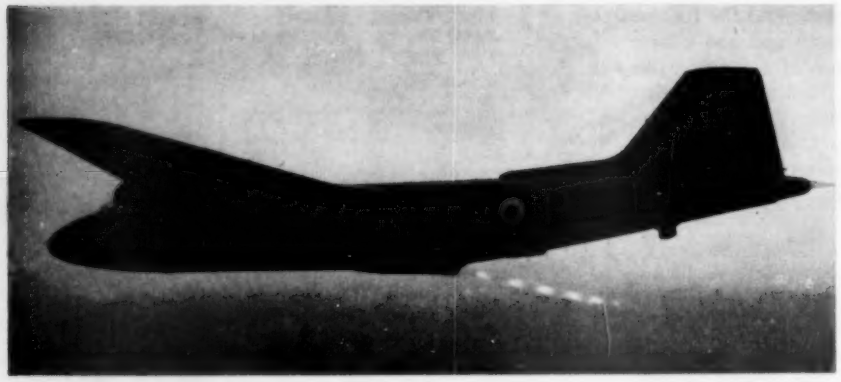

FIGURE 10. External view of Canberra showing position of Spectre.

the point of injection. This was virtually impossible with the multiple injectors originally fitted but became feasible when each bank was replaced by a single poppet injector.

In the original design, H.T.P. was led from the coolant jacket through a complicated fabrication, around the cylindrical decomposers and fuel injectors, before it was piped away to the 2nd stage pump. This arrangement involved a rather difficult liquid/gas seal at the head of the chamber which often failed, either allowing H.T.P. to leak into the chamber or combustion gases to leak into the coolant space. Furthermore, it was suspected that stagnant areas existed in the coolant space around the chamber head where H.T.P. decomposed and led to unstable running. The head of the combustion chamber was therefore redesigned so that the area around the decomposers and injectors was left uncooled, the H.T.P. being taken out of the coolant jacket at the forward end of the combustion chamber itself. This necessitated certain changes to the seals around the injectors, but at the same time greatly simplified the chamber head seal which, from then on, gave practically no trouble.

As a part of this redesign, a steam distributor plate was fitted into the head of the combustion chamber. This plate, looking very much like a domestic colander, collected all the steam from the turbine and the three separate decomposers and distributed it evenly over the chamber cross section.

When attempting to carry out long runs at low thrust, persistent combustion chamber burning near the throat section was experienced. This was attributed to streaky combustion, due to the three-point injection system. Systematic experiments taking out one injector at a time proved this point. A single central injector was therefore fitted to replace the three previously used. Kerosine was led into the combustion chamber through a pipe just downstream of the turbine. From there it was led to a mushroom injector which protruded through a central hole in the steam distributor plate. The injector contained a large number of radial holes which sprayed kerosine on to a spun-over target plate. A non-return valve was built into the injector head to prevent any burning or explosion within the injector itself.

Quite apart from the effect of uneven combustion, it was found that burning of the combustion chamber wall often occurred under one of the coolant vanes, due to a local hot spot being formed. To prevent this the vanes were removed from the combustion chamber and instead were cast on the inner wall of the associated filler block and small slots were cut in the vanes to allow a small flow of H.T.P. across them and thus prevent any local overheating.

After all these improvements had been well tested, and we were about to attempt a special category test with some confidence, an H.T.P. pump explosion occurred although over 50 hours successful running had been carried out with the design. The explosion was attributed to H.T.P. overcoming the complicated seal arrangement and mixing with oil in the neighbouring bearing. It was decided that to overcome this trouble completely vented open spaces between the H.T.P. and oil parts of the pumps were necessary. To find room for this redesign it was necessary to put the sealing arrangement between the two pump bearings and to lubricate the bearing nearest the pump impeller with H.T.P., an unplasticised P.V.C. rod bearing being developed for this purpose and giving practically no trouble afterwards. The new arrangement of pump, together with most of the other changes to which reference has been made are shown in Fig. 9, which indicates the form of engine which was first cleared for flight over a 2,000 to 7,000 lb. thrust range in November 1956.

Flight Testing

Flight testing of the Spectre began in December 1956 in a Canberra which had been specially modified as a flying test bed. This modification consisted of building a mounting in the rear part of the bomb bay so that the engine could be installed to fire slightly downwards. Into the forward part of the bomb bay was built a 600-gallon P.V.C. lined H.T.P. tank, a fuel tank being fitted above and slightly ahead of the engine. A closed circuit television system was fitted with a camera in the engine bay so that the pilot could view the engine during flight. The underside of the fuselage to the rear of the rocket nozzle was protected by means of a stainless steel sheet, and solder sticks were attached to the fuselage so that the flame boundary could be approximately determined. Fig. 10 shows the Canberra with a Spectre engine installed.

Before any flying took place, a number of cold ground runs, *i.e.* on H.T.P. alone, were carried out, the engine being fired into a pit over which the aircraft was wheeled. Very little aircraft trouble was experi-

enced during this phase although there was some evidence that some trouble from noise and vibration might be met when full thrust hot running was attempted. These fears were later justified.

A series of 6 flights were carried out during which the engine was run cold up to a thrust of about 4,000 lb. During these flights experience was obtained on the general handling of the engine as well as its initial starting characteristics, its ability to change thrust and to restart during flight.

A series of hot ground runs were then carried out and at this stage our fears regarding the effect of the noise from the Spectre on the Canberra structure and equipment were justified. The effect of noise manifested itself in a number of ways. Fuselage rivets were loosened and some brackets attaching stringers to ribs were cracked. Cracks also appeared in the elevator skinning and a bracket supporting an electrical junction box in the rear part of the fuselage broke away. Even more seriously the tail plane actuator began to give trouble. Fortunately, all these failures were confined to the part of the fuselage to the rear of the rocket exhaust. As much electrical equipment as possible was therefore re-sited farther forward and the brackets holding the remainder were strengthened. Improved limit switches were fitted to the tail plane actuators, and since it had been shown that the effects were most serious under this condition, ground running was kept to a minimum and when it was carried out a protective sound insulating muff was attached to the lower side of the rear fuselage.

Flight tests with the Spectre running "hot" were begun in February 1957 and some 29 flights were carried out. As in the case of the previous tests with the engine running cold, an investigation into general engine handling was carried out, paying particular attention to thrust control and re-starting. On the ground some trouble had been experienced due to the engine becoming overheated on shutdown as a result of the residual heat in the hot parts of the engine raising the temperature of the stagnant H.T.P. left in the coolant jacket. Because of this, the lower engine cowling was generally left off during ground runs. In the air, however, because of generally cooler ambient conditions, no similar trouble was experienced.

Following the completion of a satisfactory flight programme in the Canberra, a Spectre was installed in an S.R.53 aircraft early in 1957 and a series of ground runs carried out. These at once brought us back to the heat soak problem when the engine was shut down. On one occasion the H.T.P. left in the engine overheated and decomposed so violently that some of the associated coolant pipes were ruptured.

To investigate this problem a further series of test bed firings were carried out. These were augmented by a number of firings in a fuselage rear end specimen which was exactly similar to the S.R.53 and installed on our test site at Hatfield. The problem of heat soak was eventually overcome by improving the ventilation of the engine bay to produce cooler conditions, and in addition by changes which were made to the propellant system to permit a convective flow of H.T.P. on shut-

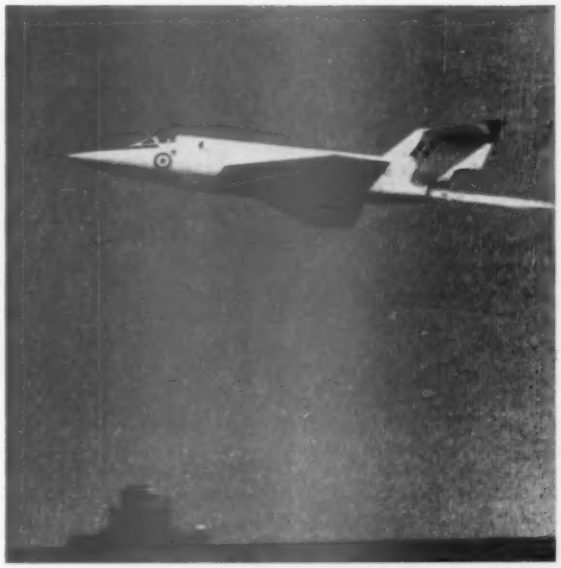

FIGURE 11. External view of S.R.53.

down, thus reducing the effect of stagnant pockets. The most effective change was, however, to use main tank pressure to maintain a small flow of H.T.P. through the engine on shutdown, this flow being discharged through an overboard vent. This prevented stagnant H.T.P. becoming overheated, but to further reduce this risk, it was first of all thought necessary to run the engine for a short while on peroxide alone before shutting it down in order to generally reduce temperatures. This procedure was however eventually found to be unnecessary. It was ascertained the H.T.P. bleed required to keep peroxide temperatures down was very small, and further testing showed that it could be shut off completely about 10 mins. after shutdown.

The first S.R.53 flight took place in May 1957 and was quite successful except for the inability of the engine to re-start during the flight. This was eventually traced to some valve mal-functioning which was subsequently put right by modification. A considerable number of S.R.53 flights have been made up to the present time and except for some minor troubles the Spectre has behaved quite well. Fig. 11 shows a view of the S.R.53 with the rocket engine running.

Three fairly major changes were, however, made to the engine during that period. While running an engine to an obsolete standard at Hatfield some deliberate mishandling tests were performed which resulted in the fuel entering one of the catalyst packs and causing an explosion on a subsequent re-start. Although a similar occurrence was considered unlikely on the standard of engine flying in the S.R.53, a modification was thought necessary to prevent it completely. This consisted of a dumping system which completely drained the fuel injector when the engine was shut down and therefore removed the possibility of any fuel running from the injector and finding its way into a catalyst pack.

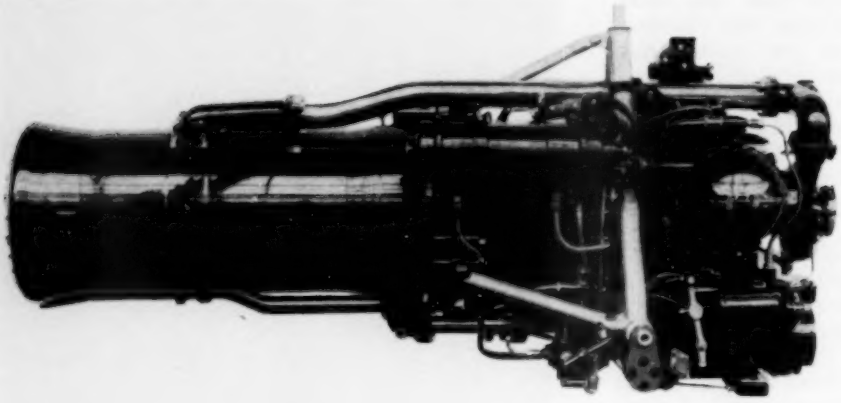

FIGURE 12. External view of Spectre V.

The second change was to start the engine, not from its starting system, but by means of the aircraft main tank pressure. This resulted in a rather slower initial start but since it meant that the engine was both primed with H.T.P. and started by the same operation, it was felt to be more reliable especially for re-starting the engine after a period of heat soak. It also meant that the starting system with its inevitable extra weight and complication could be deleted.

It was originally thought that for long runs the temperature of the oil in the gear box would rise prohibitively especially as this oil was used for cooling the turbine seal where there is a fairly high transfer rate. To keep the oil cool it was passed through an oil to H.T.P. heat exchanger. Kerosine could not be used for this purpose since the engine had to be capable of running on H.T.P. alone and there was then no kerosine flow. The oil to H.T.P. cooler was always looked on as a potential hazard although it never gave any trouble whatsoever. Some tests were, however, carried out which showed that even in the most unfavourable conditions the oil temperature would remain just acceptable even without cooling. As a result the heat exchanger was left off, once again with some weight saving and reduction in complication.

Future Developments

Development of the Spectre I has now reached a stage where only minor matters demand attention. Experience with this first mark of engine has, however, shown how the design can be improved in a number of ways and many such modifications are being built into later engines.

By a general re-arrangement of components it has been found possible to reduce the weight and complexity. As an example, it has been possible by locating the combustion chamber in a different way and at the same time changing its material, to revert to high pressure cooling as was originally intended on the Spectre I. This eliminates one of the H.T.P. pumps and greatly simplifies the gear box. A number of parts, originally made in steel are now made in light alloy and some of the more difficult seals in the Spectre I have been eliminated by redesign. These modifications, together with many others, are incorporated in the Spectre IV and V, one of which is shown in Fig. 12.

This engine is much lighter than the Spectre I, but there are still further improvements which could be included which would reduce the weight and size even more. For example, the pumps with only a very small loss in efficiency could be mounted on the same shaft as the turbine. This would eliminate the gear box completely and with it the need for any oil lubrication since all the bearings could then be propellant lubricated, following the practice already employed on the Spectre I. The separate combustion chamber and coolant jacket could be replaced by a fabricated one-piece multi-channel chamber, the durability of which has already been demonstrated with H.T.P. cooling over a wide thrust range. All these changes could be made using no new principles but by using a logical development of techniques which have already been proved by extensive running on existing engines.

Inertial Navigation

by

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INERTIAL NAVIGATION is a completely new approach to the navigational problem initiated to a very large extent by the military requirement for a blind navigational system which could not be jammed by, nor give actual assistance to, any potential enemy. It relies for its operation on principles which were understood by Newton, but the practical realisation of a working system has become possible only by the intensive development in both the design and manufacturing techniques of gyroscopes and accelerometers. This development work has, to a considerable extent, been stimulated by Dr. Draper of the Massachusetts Institute of Technology and, although he may not be the inventor of inertial navigation as such, there is little doubt that but for the work carried out under his direction, inertial navigation would still be little more than a dream.

Inertial navigation depends basically on the simple fact that if we can measure the acceleration vector of a body in any convenient axis system, then by carrying out the suitable integration processes we can determine its path in space, its position and its distance from its initial position.

Acceleration, as is well known, is a quantity which can be measured without reference to the external environment by measuring the force applied to a small body which is constrained to move with the main part of the vehicle. Such a device will also detect forces which do not cause a movement of the main vehicle; for example, accelerations due to gravity and due to Coriolis effects. However, these can be compensated for fairly readily, although there are complications such as the stability of the overall system, which must not be neglected. This very simple statement might lead one to suppose that the heart of any inertial navigation system is the accelerometer. Oddly enough, this is not quite true, the *prima donna* of the inertial navigation world being, in fact, the gyroscope. This arises because of the importance of defining the axis system and from the fact that the earth, over which the navigation is assumed to take place, is roughly spherical, the direction of gravity being always radial.

It is, in fact, possible to make an inertial navigator containing no accelerometer more accurate than a spirit level and such a navigator, or at least a relatively simple adaptation of it, might even have practical application.

It is convenient to begin the discussion on the general principles of inertial navigation by discussing systems which, in the main, are more suitable for applications over very long ranges, although such systems are, in fact, the most difficult to engineer. It is well known that by making use of the properties of gyroscopes, a stable platform may be constructed using either three single-degree of freedom or two two-degree of freedom gyros. Because such a platform is servo-driven, relatively large disturbing torques may be applied to it without displacing it from its fixed orientation in space. The only way in which this can be effected is by applying torques to the gyros themselves, upon the application of which the platform will precess at a rate determined by the applied torque and the angular momentum of the gyro.

Taking the simple case first in which no disturbing torques are applied to the gyroscope, the platform will clearly remain in a fixed orientation with respect to the fixed stars, and therefore the platform may be used instead of the stars in our navigational system, and by measuring suitable angles and knowing the time and the direction of gravity, we may navigate in precisely the same way that navigators have been using for many years. The important advantage that has been gained, of course, is to avoid any direct reference to the fixed stars. We have, so to speak, built the universe into a black box which can be stowed conveniently on an aircraft or ship and treated to the abuses which are common in such circumstances.

Provided that our vehicle is not being subjected to any significant accelerations, it would be satisfactory to measure the local vertical by means of a spirit level or similar device, as has been done in the sextant for years. If, however, as is more usual, the vehicle is being accelerated, then an alternative method of finding the true vertical must be devised. Schuler showed that if a pendulum could be constructed whose effective length was equal to the radius of the earth, then an acceleration of the point of suspension would not cause a disturbance to the bob, the line joining the two being always parallel to the earth's gravitational field. Such a pendulum can be physically realised by means of the arrangement shown in Fig. 1. Here, a gyroscopically controlled platform carries an accelerometer whose output is integrated with respect to time, and then used to apply a torque to the gyroscopic element. Assuming for the moment that both platform and earth are stationary, any tilt of the platform will result in a steadily increasing torque being applied to the gyroscope and hence a steadily increasing precession rate and, therefore, a steadily decreasing angle of tilt of the accelerometer. Such a system, given suitable constants, can be made to have a period of about 84 minutes. It is not difficult to show that such a pendulum can be

The sixth lecture to be given to the Guided Flight Section of the Society—on 24th November 1958.

made to meet the same equations as a simple pendulum having a length equal to the radius of the earth and Schuler's requirements are thereby met.

To keep the platform truly horizontal, it is necessary to apply precessional torques to the gyroscope so that it precesses at the angular rotational rate of the earth, while if the platform is moving rapidly over the earth's surface, the effect of Coriolis accelerations must also be allowed for by injecting the appropriate signal into the integrator in parallel with the accelerometer signal.

So far as the main space stabilised platform is concerned, it can readily be seen that the effect of gyro wander rate will be to cause the entire platform to rotate with respect to inertial axes at that same rate: a wander rate of, for example, one degree per hour being exactly equivalent to an angular velocity around the earth of one degree per hour, that is approximately sixty miles per hour. Errors in the Schuler pendulum are of a rather more complex nature. A steady wander rate in the gyro, due either to the gyro itself or to small errors in earth's rate correction, cannot of themselves cause a steady error and the pendulum will always seek the vertical. Errors in the Coriolis correction cause a departure from the vertical, but the magnitude of these terms for speeds at present considered practicable is so small that little difficulty is obtained in providing the necessary corrections. However, any sudden change of conditions inside the pendulum tend to disturb it momentarily and since one has gone to a great deal of trouble to make the pendulum effectively frictionless, it will continue to swing with its period of 84 minutes and the observed position will, therefore, have a cyclic error with this same period.

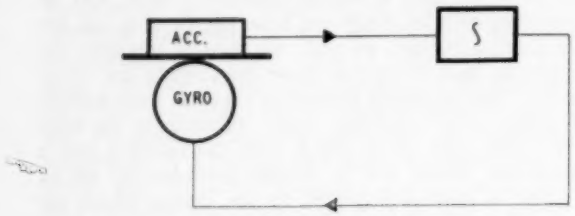

FIGURE 1.

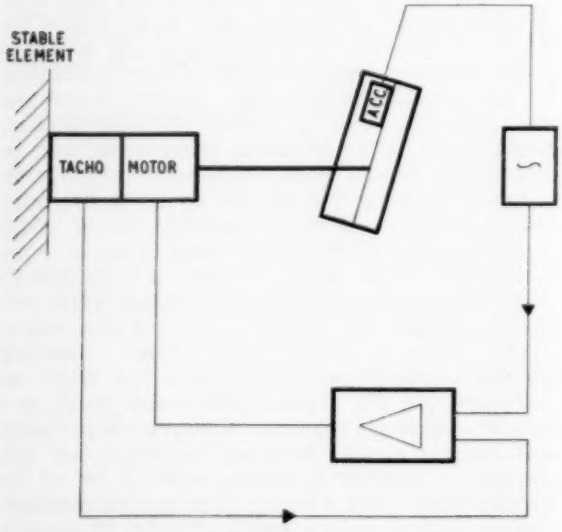

FIGURE 1(*a*).

Since we can never be certain that such disturbances will not arise from time to time, it is essential to provide some means of obtaining suitable damping. Such damping terms may be obtained with the aid of some external and independent measure of either acceleration or velocity. Unfortunately, however, the relatively inaccurate nature of such information tends in itself to disturb the pendulum and the problem of obtaining a suitable compromise in any given set of circumstances is a most severe one.

So far the best results have been obtained using Doppler radar to give an independent measure of velocity, but the overall system is complex.

Another approach to the problem is the use of non-linear elements inside the pendulum system to limit the amplitude of oscillation to some acceptable value. The presence of such non-linear elements, however, renders the analytical problem extremely difficult and in most cases completely intractable, although it is fortunately a fairly simple matter to study any such systems with the aid of analogue simulators which have already been proved most powerful tools in examinations of this sort. There is, however, still considerable scope for ideas and investigation in this particular aspect.

The system so far described has considerable advantages over other systems in that, provided the vehicle is subject only to rela.ively modest accelerations, it is dependent for its accuracy only on the gyroscopes utilised.

As already discussed, errors in the applied precessional torques to the gyroscopes are not of major importance, provided that they remain constant. Errors in the accelerometer and integrator will affect the period of the pendulum which will, therefore, tend to be disturbed by accelerations in proportion to its deviation from a true 84-minute period and errors in applying the torque to the gyroscope from the integrators will have substantially the same effect. We are not, therefore, concerned with an enormous degree of accuracy in any component other than the basic gyro, of which the system as described uses at least five.

Since gyroscopes are at the present time very expensive items, there is some merit in attempting to reduce the number. However, we shall not be able to do so without incurring penalties in other directions.

One way in which the 84-minute pendulum system can be successfully combined with the space stabilised system is simply to measure the angle through which the 84-minute platform has been turned by integrating the signal applied to the torque-motor on the gyros. Since the total angle through which we must turn the 84-minute platform to maintain it horizontal is the sum of the angular rotation of the earth in a given time, plus the angular movement of the platform about the earth's centre in that same time, the integral of the precessional rate applied from the integrator will give us angular distance moved about the earth's centre.

In this case, however, we are critically dependent on the characteristics of the motor used to apply precessional torques to the gyro. Clearly such forces are essentially of an analogue nature, the torque always arising from an electric motor of some kind in which the torque output is proportional to the strength of a magnet, multiplied by the current flowing in a given coil.

It is clearly difficult to provide a high degree of linearity, a low zero error and a day-to-day constancy in any such motor. Furthermore, the earth's rate correction must now be made appreciably more accurately than the basic wander rate of the gyros, as any errors in this will show up directly in the distance-gone measurement. However, as opposed to this disadvantage, the three-gyro system uses an inherently simpler gimbal system and, of course, fewer gyros and may therefore be made a rather more rugged and, possibly, a more reliable device.

Alternatively, the main gyro package may be allowed to remain fixed in space, the 84-minute pendulum being programmed from it as in Fig. 1(*a*). This leads to a five gimbal three-gyro system in which the accuracy requirements of the gyro torque motor are transferred to the Velodyne driving the extra gimbals.

It is on the whole simpler to make a high precision Velodyne than a high precision torque motor and there is a good deal in the argument that all secondary functions should be avoided in precision components, such as gyros and accelerometers.

It will be noted that in the five gimbal system, the gravitational vector rotates with respect to each gyro, so the unbalances cancel every 24 hours, whereas in the three gimbal system the gravitational vector is constant —and so may be compensated for. Possibly more important is the fact that g^2 terms due to gravity will not change with time.

An important variant of these systems makes a much more and direct use of the rotation of the earth. By sensing this rotation by means of the rate gyroscopes the platform may be made to align itself parallel to the earth's spin axis and then home on to the Pole Star in a manner exactly analogous to the homing of a Naval gyro compass to the North. Such a system would seek out the Pole Star immediately after switching on and would, therefore, indicate both latitude and azimuth without the necessity for setting these in as initial conditions. However, it suffers from the same defect as the conventional gyro compass. If the vehicle possesses a northerly velocity it has an angular rotation about the earth's centre, with an axis of spin at right angles to the axis of spin of the earth. The simple system is incapable of resolving one rotation from the other and the platform therefore homes to a false point, the magnitude of the error being dependent on the northerly component of velocity. It is possible to correct this effect to some extent by applying appropriate torques to the gyros, proportional to northerly velocity, this velocity being obtained from the 84-minute pendulum. However, because the earth's angular velocity is so low, quite modest linear velocities must be known to a very high order of accuracy if the overall system is to compete with the free gyro system. A very large burden, therefore, is placed on the linearity of both accelerometer, integrator and torque motor, even under non-accelerating conditions and the system is quite impracticable at aircraft velocities, although it may have applications to surface vessels.

At the very low speeds involved in this type of vehicle the automatic aligning feature can be a considerable advantage, although the longitudinal axis must still be of the highest possible precision. However, its use in initial alignment may be important.

Reverting to the three-gyro system previously described, in which no attempt is made to align with the Pole Star, it can readily be seen that the signal applied to the gyro torque motor from the integrator will be proportional to the velocity of the vehicle over the earth's surface. For times of flight of less than about one hour, the damping of the 84-minute pendulum becomes of negligible importance as no method of damping can have much influence on the first half cycle. If durations of less than 30 minutes are being considered, then the error due to an initial disturbance of the pendulum will be roughly proportional to the cube of time. With these relatively short-range devices, the accuracy of the accelerometer and integrator tends to become of increasing importance relative to the accuracy of the gyroscope, although, of course, the accuracy of all components can be degraded relative to that required for the long-range cases. In the limit for very short periods and distances such that the earth can be considered as flat, it becomes unnecessary to precess the gyro at all, and quite crude components can be utilised. Such systems have, in fact, been proposed as a means of measuring the take-off performance of aircraft where the time interval is less than one minute and the distance of the order of a few thousand yards. In this case, gyroscopes of quite conventional accuracy, say, of the order of ten degrees per hour, may be used and the overall accuracy is determined almost entirely by the accelerometer and integrators for which an overall accuracy of 0·1 per cent is not at all unreasonable.

Whenever a new technique is introduced, it is common experience that every effort is made to utilise the technique to its maximum advantage and the inertial navigator designer is, therefore, always struggling to make the best possible use of the components and techniques available to him. There is no doubt, however, that at the present time and probably for some time to come, the limitations on an inertial navigator's performance arise in the main from the performance of gyroscopes and accelerometers. It is extremely important that none of the auxiliary computing gear should be allowed to impose a significant deterioration on the best performance which can be obtained from the gyroscopes involved.

Inertial navigation presents an interesting problem from the computing point of view. Some calculations must be carried out to the highest order of precision. There are, however, a vast quantity of second order terms which tend to arise, particularly in short-range and crutched systems, which need only be computed to an accuracy of a few per cent. Coriolis terms are typical in this respect.

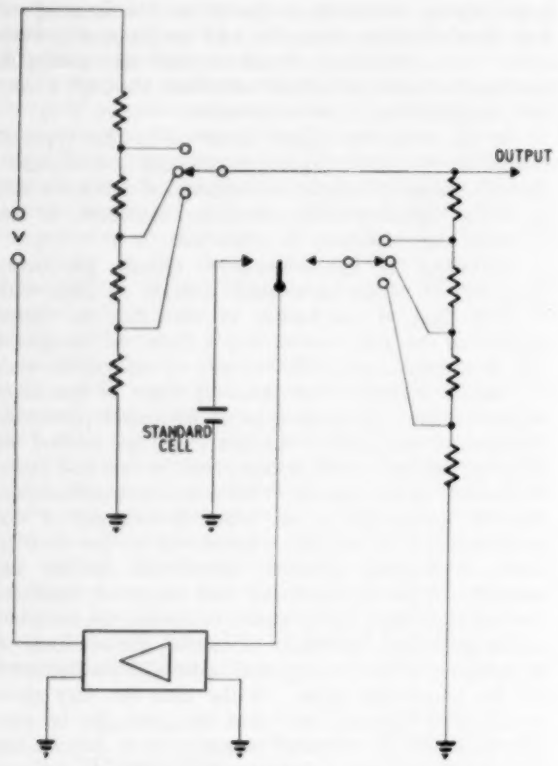

FIGURE 2.

A digital computer is undoubtedly capable of carrying out the high precision computations to any order of accuracy required. Unfortunately, however, it becomes difficult to insert the second order terms in a reasonably convenient way, although it is by no means impossible. We are also faced with a number of analogue/digital and digital/analogue conversions. With an analogue system, however, equipment can be organised so as to compute each term only to the required order of accuracy; the decision to use analogue or digital computation methods, which has caused considerable argument in other spheres in the past, has to be made considering the precise requirements of any system on its own merits. Commercially available gyroscopes have, at the present time, only a moderate order of precision and analogue computing is possible if we make the reasonable assumption that system performance is to be unaffected by the inaccuracies of the computer. The analogue computers required are nevertheless of quite high precision and the manufacture of these devices on any reasonable production basis presents some interesting problems.

The design of satisfactory test equipment, both for production and maintenance purposes, needs to be most carefully considered. Many voltage measurements must be referred back to the standard cell, time measurements must be made with respect to a quartz crystal, and other electrical and mechanical quantities must be measured with the highest possible accuracy. These measurements are not particularly difficult in the laboratory where highly skilled personnel, with a reasonable amount of time at their disposal, are available. However, on a production line we must frequently rely on a relatively unskilled girl operating with the minimum possible supervision and testing the maximum number of units per hour.

To illustrate this point, I should like to describe the test equipment used in final calibration of two different types of integrator; the first, a Miller type integrator of a purely electronic nature, and the second a Velodyne integrator using a high precision tachometer as the feedback element. To enable these units to be tested, the first requirement is an accurately known voltage source which can be adjusted to a number of different known values and which has an output impedance so low that normal variations in the load connected to it do not sensibly affect the output. This can be achieved by means of a system shown in Fig. 2.

A voltage which is stabilised by conventional methods to about one per cent is maintained across a chain of resistors. An appropriate proportion of this voltage is selected by means of a switch connected to the chain. The output from this switch ultimately forms the output of the power supply. An appropriate proportion of this output is selected by means of a second selector switch ganged to the first, the proportion being very accurately controlled by means of resistors of the highest possible quality. Any difference existing between the selected proportion and the output of a standard cell is detected by means of a high speed chopper which converts the error signal into a.c. which is then amplified some ten million times, rectified and added to the mains supply voltage across the resistor chain. By suitable selection of the chopper, the error introduced from this source can be held as low as 50 microvolts. Because of the high amplifier gain, the output impedance of the power unit is only a small fraction of an ohm and the change in output due to load changes is negligible. The accuracy of the system is thus determined by the accuracy of the resistor chain, the accuracy of the standard cell and the error introduced by the chopper. The temperature-sensitive provision is made for comparing the output with a second standard cell. It is possible with this power supply to obtain voltages in the range 1-100 volts accurate to better than one part in 10^4.

To test a Miller integrator, the feedback condenser is first of all shunted by a low value of resistance while maintaining zero input to the device, so that the output is reduced to zero. The selected voltage is then applied to the input, the shunt resistor removed across the condenser and the unit allowed to integrate for a fixed period of time. This time is controlled by a quartz crystal with a suitable dividing arrangement and is calculated to give an output of, say, 50 volts at the end of the selected time. The input to the integrator is then reduced to zero and the output compared with a standard 50 volt signal obtained from the precision power supply. Any difference existing between the two voltages is readily measured and the necessary adjustments made to the integrator time constant until, on repeated runs, the measured error signal falls to zero.

The arrangement used for Velodyne will not accelerate or decelerate instantaneously. Calibration of these units may, therefore, be carried out by unskilled personnel in a very short space of time and it is quite simple to introduce additional checks, such as drift of the output, while the integrator is on the same test rig.

A number of tests have been devised to check the day-to-day repeatability of the test equipment itself and figures in excess of one part in 10^5 have been realised, although the absolute accuracy cannot exceed one part in 10^4.

It is frequently argued that inertial navigation is likely to be of interest only to military activities because of the high cost and complexity of the equipment. In general, the equipment tends to be complex when we are attempting to obtain the maximum possible accuracy from rather inferior gyros and accelerometers.

If one considers the possibilities on the basis that really high-grade gyroscopes and accelerometers become available at a not too exorbitant cost, then a rather different picture is presented. In the first place, the apparatus can become very simple because axis systems can be chosen which do not involve large amounts of computation. If we consider the system applied to an aircraft, then the stable platform automatically gives us attitude information and heading information, thus enabling us to dispense with some of the rather complicated systems which now exist.

It would appear to be quite feasible to obtain velocity information to the same order of accuracy as that obtained from commercially available Doppler equipments. The navigator could then be utilised to present track information and positional information, possibly in the form of latitude and longitude, directly to the pilot or navigator who would correct the positional information manually as and when more precise fixing information became available from other sources. The availability of such a navigator on the aeroplane would enable instruments, such as take-off monitors, to be provided in a very simple manner and it could also be used as a smoothing element for VOR systems so as to eliminate difficulties presented by the cone of confusion when flying over a VOR station and to smooth I.L.S. approach beams without incurring stability problems due to time delays.

The advantages of carrying such a navigator appear, therefore, to be such that there is some reasonable hope of seeing them in airline service in the not too distant future.

SUMMARY OF DISCUSSION

Some time was spent on the Civil applications of Inertial Navigation and some doubt was expressed as to the necessity for such a system in view of the abundance of radio aids which were simpler and probably more accurate. It was, however, pointed out that on some routes, particularly in Africa and over the Pole, these radio aids were relatively infrequent, and not particularly reliable.

It was agreed that components for such a system were not at present available, and that the cost and weight of such a device was accordingly dependent on these components. However, given components of adequate accuracy, it seemed probable that a system could be chosen in which complexity was held to a small value by a suitable choice of axis systems.

Views were also expressed on the desirability of allowing crews to monitor such an Inertia system rather than attempt to provide other monitoring systems from other aids. The speakers pointed out the very difficult environmental conditions under which Inertial Navigators for military application have to function. However, the complexity of this device in itself precluded any maintenance operations in the field, and if the unit was hermetically sealed, and opened only in a reasonably equipped laboratory, dust and dirt present very little problem.

Vibration still represents a significant factor, and improved means of isolating the complete system from the vibration of the vehicle were urgently needed.

On the question of testing precision components, the methods described in Dr. Cawood's paper* were reiterated, and the difficulties of obtaining steady accelerations for testing gyroscopes and accelerometers were discussed. The use of centrifuges to obtain these accelerations was being tried, but attainment of accuracies greater than that of 1 in 10^{-4} was difficult, and the testing of gyroscopes especially so, because of the rotations associated with the centrifuge.

*W. Cawood. Some Design Problems in Inertia Navigation. *Journal of the Royal Aeronautical Society*, p. 704, October 1958.

TECHNICAL NOTES

On the Evaluation of Certain Finite Sums of Progressive Products

by

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THIS NOTE is concerned with the evaluation of the finite sum

$$F_m=\sum_{r=1}^{n}(-1)^{n-r}\binom{n-1}{n-r}(r+Z_1)(r+Z_2)\ .\ .\ .\ (r+Z_m)\ .\quad (1)$$

where the m quantities Z_i are arbitrary and where

$$\binom{n-1}{n-r}=\frac{(n-1)!}{(n-r)!\,(r-1)!}$$

is the binomial coefficient in a series of n terms. Summations of this kind appear in the evaluation of matrix products involving the reciprocal of order n of a segment of a Hilbert matrix or of a generalised Hilbert matrix.[1]

Such products are found, for example, in the representation of a lifting aerodynamical surface by a set of horseshoe vortices.[2]

CONSTITUENT SUMS

Let the m factors $(r+Z_i)$ be multiplied out, and let P_1 be the sum ΣZ_i, P_2 the sum of the products taken in pairs, and so on; then

$$F_m=\sum_{r=1}^{n}(-1)^{n-r}\binom{n-1}{n-r}\{\,r^m+P_1r^{m-1}+P_2r^{m-2}+\ .\ .\ .\ +P_m\,\}$$

$$=G_m+P_1G_{m-1}+P_2G_{m-2}+\ .\ .\ .\ +P_mG_0\ .\quad .\quad .\quad (2)$$

where

$$G_s=\sum_{r=1}^{n}(-1)^{n-r}\binom{n-1}{n-r}r^s\quad .\quad .\quad .\quad .\quad .\quad .\quad (3)$$

is a constituent sum which we proceed to evaluate.

Let $\quad g_s(x)=(xD)^s\,x\,(x-1)^{n-1}$

$$=(xD)^s\sum(-1)^{n-r}\binom{n-1}{n-r}x^r$$

where the symbol Σ is understood to sum with respect to r from 1 to n. The operator xD changes x^r to rx^r; hence in view of (3),

$$G_s=g_s(1)\ .\quad .\quad .\quad .\quad (4)$$

We now use Leibnitz expansions to obtain an alternative form for $g_s(x)$; progressive differentiation of the products yields

$$g_s(x)=(xD)^s\,x\,(x-1)^{n-1}$$
$$=(xD)^{s-1}\,[(n-1)\,x^2\,(x-1)^{n-2}+x\,(x-1)^{n-1}]$$
$$=(xD)^{s-2}\,[(n-1)\,(n-2)\,x^2\,(x-1)^{n-3}+$$
$$+3\,(n-1)\,x^2\,(x-1)^{n-2}+x\,(x-1)^{n-1}]$$

and so on.

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Evidently we may write

$$g_s(x)=\frac{(n-1)!}{(n-s-1)!}\,x^{s+1}\,(x-1)^{n-s-1}+$$
$$+a(s)\frac{(n-1)!}{(n-s)!}\,x^s\,(x-1)^{n-s}+$$
$$+b(s)\frac{(n-1)!}{(n-s+1)!}\,x^{s-1}\,(x-1)^{n-s+1}+\ .\ .\ .+x\,(x-1)^{n-1}\quad (5)$$

If we now put $x=1$, we obtain, in view of (4), the value of G_s; it consists of at most one term, namely that for which in (5) the index of $(x-1)$ vanishes. Thus

$$\left.\begin{aligned}G_s&=0 && s<n-1\\ G_{n-1}&=(n-1)!\\ G_n&=(n-1)!\ a\ (n)\\ G_{n+1}&=(n-1)!\ b\ (n+1)\end{aligned}\right\}\quad .\quad (6)$$

and so on. We now require to evaluate the functions a, b, etc.

EVALUATION OF THE CONSTITUENT SUMS

Consider equation (5); if it is operated on by xD we obtain on the left $g_{s+1}(x)$; the two forms for the right hand side then give at once the regression formulae

$$a(s+1)-a(s)=(s+1)$$
$$b(s+1)-b(s)=sa(s)$$
$$c(s+1)-c(s)=(s-1)\,b(s)$$

which we require to solve in the form

$$\left.\begin{aligned}a(n)-a(n-1)&=n, && a(1)=1\\ b(n+1)-b(n)&=na(n), && b(2)=1\\ c(n+2)-c(n+1)&=nb(n+1), && c(3)=1\end{aligned}\right\}\quad (7)$$

and so on. These equations may be solved in a variety of ways. Substitution of an appropriate polynomial is a very direct way; alternatively, summation of all terms can be used. Clearly $a(n)$ is the sum of the natural numbers; thus

$$a(n)=\Sigma r=\frac{(n+1)\,n}{2}\ ;$$

then

$$b(n+1)=\Sigma\,\frac{(r+1)\,r^2}{2}$$

which may be evaluated from the known sums of the squares and cubes of the natural numbers. The author has used the following method, which is illustrated here for the evaluation of $b(n+1)$. The method is quoted because of its flexibility; it can be used to work by inspection towards any desired result involving summations of the kind represented by $a(n)$, etc. For example, the sums of the powers of the natural numbers are easily found by it.

$$\text{Let} \qquad f(x)=1+x+\ \ldots\ +x^{p-1}=\frac{x^p-1}{x-1} . \qquad (8)$$

Write y for $(x-1)$;

$$\text{then} \quad f(1+y)=\frac{(1+y)^p-1}{y} .$$

$$=p+\frac{p(p-1)}{2}y+\frac{p(p-1)(p-2)}{2\times 3}y^2+\ \ldots$$

Accordingly, at $y=0$, we have

$$\left.\begin{aligned} f(1)&=p \\ f'(1)&=p(p-1)/2 \\ f''(1)&=p(p-1)(p-2)/3 \end{aligned}\right\} \quad . \quad . \quad (9)$$

and so on. If we now choose $p=n+2$, we have from (8)

$$f(x)=1+x+\ \ldots\ +x^{n+1},$$

$$f'(x)=\quad 1+\ \ldots\ +(n+1)x^n;$$

the operator xD now gives

$$xf''(x)=\Sigma(r+1)rx^r,$$

whence $xf'''(x)+f''(x)=\Sigma(r+1)r^2x^{r-1}$.

Putting $x=1$, we obtain

$$b(n+1)=\Sigma\frac{(r+1)r^2}{2}=\frac{f'''(1)+f''(1)}{2}$$

which in view of (9) gives

$$b(n+1)=\frac{(n+2)(n+1)n(3n+1)}{24} .$$

In this manner, or otherwise, we find that the solutions of the regression formulae (7) may be written

$$\left.\begin{aligned} (n-1)!\,a(n)&=\frac{(n+1)!}{2} \\ (n-1)!\,b(n+1)&=\frac{(n+2)!}{2\times 4}\left(n+\frac{1}{3}\right) \\ (n-1)!\,c(n+2)&=\frac{(n+3)!}{2\times 4\times 6}(n^2+n) \end{aligned}\right\} \quad . \qquad (10)$$

and so on.

THE VALUE OF F_m

In view of equations (2), (6), and (10) we have finally

$$F_m=0 , \qquad m<n-1,$$

$$F_{n-1}=G_{n-1} ,$$

$$F_n=G_n+P_1G_{n-1} ,$$

$$F_{n+1}=G_{n+1}+P_1G_n+P_2G_{n-1} ,$$

$$F_{n+2}=G_{n+2}+P_1G_{n+1}+P_2G_n+P_3G_{n-1} ,$$

and so on, where

$$G_{n-1}=(n-1)!$$

$$G_n=\frac{(n+1)!}{2}$$

$$G_{n+1}=\frac{(n+2)!}{2\times 4}\left(n+\frac{1}{3}\right)$$

$$G_{n+2}=\frac{(n+3)!}{2\times 4\times 6}(n^2+n)$$

$$G_{n+3}=\frac{(n+4)!}{2\times 4\times 6\times 8}\left(n^3+2n^2+\frac{1}{3}n-\frac{2}{15}\right)$$

$$G_{n+4}=\frac{(n+5)!}{2\times 4\times 6\times 8\times 10}\left(n^4+\frac{10}{3}n^3+\frac{5}{3}n^2-\frac{2}{3}n\right)$$

and so on.

REFERENCES

1. COLLAR, A. R. (1950). On the Reciprocal of a Segment of a Generalised Hilbert Matrix. *Proc. Camb. Phil. Soc.*, Vol. 47, Part 1, 1950.
2. COLLAR, A. R. (1958). On the Accuracy of the Representation of a Lifting Line by a Finite Set of Horseshoe Vortices. *The Aeronautical Quarterly*, Vol. IX, p. 232, August 1958.

Annular Flow—A Note on the Turbulent Velocity Profile

Comment by

WILLIAM SQUIRE

(Bell Aircraft Corporation, Buffalo, New York)

IN CONNECTION with the note by Henry Barrow in the November 1958 JOURNAL (page 830) it may be of interest to call attention to a little known reference[1] which describes an extensive series of experiments. A 190 mm. pipe with 10, 35 and 100 mm. inserts was studied up to a Reynolds number of 10^6. Besides the fully developed profiles some interesting measurements showing the development of the flow in the inlet are included.

Received 28th December 1958.

The general neglect of these results which constitute an appreciable fraction of the available data for this type of flow is surprising.

REFERENCE

1. LORENZ, F. R. (1932). Uber Turbulente Stromung durch Rohre mit Kreisringformigen Querschnitt. *Mittellungen des Institutes fur Stromungsmaschinen der Technischen Hochschule Karlsruhe* 2, 26-66, 1932.

Graduates' and Students' Section

To do with Selling the Viscount

Selling the Viscount has been a team effort, we were told by Mr. D. J. Lambert, Assistant General Manager (Development), Vickers-Armstrongs (Aircraft) Ltd., in his lecture on 14th January. Every employee from Managing Director to fitter on the assembly line is involved.

The Viscount story started with the V.630 in 1945, which was quite inadequate in range and payload performance but was a very nice aeroplane. At this point it was a question of selling the idea to Vickers as the turbo-prop was then quite a step into the unknown. However Rolls-Royce were continuing Dart development and were able to promise a considerable increase in power, and the V.700 was put forward. The fate of the Viscount hung in the balance since M.o.S. had withdrawn their support, and it needed a lead from one of the airlines. B.E.A. placed their order for 20 aircraft in 1950 and this was closely followed by B.O.A.C. (for their associates) and Aer Lingus. The first big milestone was passed.

Even at this stage the future did not look too rosy since the initial orders indicated a total of 40, with a possible increase to 80, and this did not seem enough to cover development costs and reach the break-even figure.

The next milestone was the Trans-Australian Airways order. This airline, Mr. Lambert explained, was the first of the "high utilisation" airlines to favour the Viscount. An order of this nature from an airline with a reputation of choosing the best, regardless of the country of origin, was a great tribute to both aeroplane and makers.

From then on orders had come in more quickly, and Viscount sales became a straight fight between Vickers and Convair—with the Viscount having the appeal of four engines and turbo-prop, and the Convair the advantage of being a more proven airframe from a world-famous manufacturer.

The third milestone had been the Trans-Canada Air Lines order which opened up the American market, and Mr. Lambert gave an amusing account of his feelings as he set off with Mr. (now Sir George) Edwards and Mr. Clark ("none of us professional salesmen"), to try to convince T.C.A. of the Viscount's superior merits. The Capital Airlines order for 60 aircraft followed soon after.

The next stage had been the design of the V.810 series Viscount with more economical engines, greater payload and speed and longer range. This had been produced especially for the American market for those airlines which had to meet competition from the V.700! This was the fourth milestone and brought us up to date.

404 Viscount orders had been announced and 367 built. He was confident that this was not the end of the story as no other aeroplane so successfully fitted the capacity size 50–60 seats in the short range field.

Turning to the sales organisation at Vickers, Mr. Lambert told us that there were very few salesmen as such, but that selling was done by the combined effort of sales dept., representatives in the countries concerned, and whatever specialist technicians were required. To help on the technical sales side was the Civil Aircraft Development Group. About half of this group prepared route and cost analysis and considered the economic and other requirements of the potential customer, while the other half worked on generalised engineering problems which might show up on the type as a whole.

A capacity for self criticism had had to be developed as it was only in this way that you could get the operator's full confidence, and the aim was a frank and full exchange of information on service problems between all operators and the manufacturer. In this way the operator was kept happy and started selling the aeroplane for you.

Mr. Lambert ended his most interesting and entertaining talk which, he emphasised, represented his own views rather than those of his company, by answering a variety of questions. It was clear to us all that we had been listening to someone who was enthusiastic about his job and had done an immense amount to help put this country on the map as a manufacturer of civil aircraft. P.T.R.

Annual General Meeting and Film Show

The Annual General Meeting of the Section will be held at 4 Hamilton Place, W.1 at 7.30 p.m. on Wednesday 4th March. Coffee and biscuits will be served from 7.0 p.m.

The meeting will be followed by a film show.

AGENDA

1. To consider and approve the minutes of the previous Annual General Meeting.
2. To consider any matters arising from those minutes.
3. To receive the report of the Committee on the activities of the Committee and Section during the past year.
4. To elect representatives to serve on the Committee for the year 1959–60. (These are subject to approval by Council).
5. To discuss the future activities of the Section.
6. To consider any other matters connected with the affairs of the Section.

Nominations to fill the nine vacancies for the Section representatives for 1959–60 are invited. They must be both proposed and seconded and have the Candidate's agreement, and all concerned must be Graduates or Students. They should be sent to the Hon. Secretary: Mr. P. D. Stewart, 10 Abbey Gardens, Chertsey, Surrey.

Members are reminded that it is desirable for the Committee to be representative of as many firms and colleges as possible.

Lecture

Wednesday 25th February is the date on which Lt.-Cdr. D. J. Whitehead, Blackburn and General Aircraft Test Pilot, will talk on "Deck Landing of Naval Jet Aircraft."

Visits

A visit has been arranged to the R.A.E. at Bedford on Wednesday 15th April. Those interested should write to the Hon. Visits Secretary, A. R. M. Pickering, "Riverside," Vicarage Walk, Bray, Berks.

Invitation to Graduates—Informal Discussion

The Astronautics and Guided Flight Section have especially invited Graduates to take part in their informal discussion " Rocket Propulsion—Liquid and Solid," which is to be held on 3rd March at 4 Hamilton Place at 7 p.m. **Admission is by ticket only,** available to members of the Section and to Graduates on application to the Secretary, Royal Aeronautical Society, 4 Hamilton Place, London, W.1.

The prototype Vickers-Armstrongs Viscount 700.

Visit to Paris Aero Show

We are planning a cheap "all-in" trip by air to Paris for the Aero Show, leaving London on the evening of 19th June and returning on the evening of the 21st June. We hope the price will be about £12. Members who are interested should write to J. R. Cownie, 40 Sherwood Avenue, Marshalswick, St. Albans, Herts.

THE LIBRARY

Reviews

VOLUMES I-XV OF THE AERONAUTICAL JOURNAL, 1897-1911. Facsimile reprint bound in five volumes. Reproduced by permission of The Royal Aeronautical Society. *Peter Murray Hill (Publishers) Ltd., London, 1958. £67 10s.*

In the JOURNAL of the Society for November 1956 there appeared a review of the facsimile reprints, by Peter Murray Hill, of the *Annual Reports* of the Aeronautical Society, 1866-1893. They covered those years of much hope and faith, but little charity in aeronautical history.

The present volumes cover the years 1897-1911 which saw faith become a living reality, hope vacating the playing of a harp on the top of the world, and charity no longer staying at home.

They have become rare volumes, for none were ever printed more than by the hundred. During the first three years it is known that the average printing order did not exceed 300 copies. At the end of 1897 the accounts of the Aeronautical Society revealed that the paid-up membership was 37, at £1 1s. 0d. a time. The total income for that year was less than £50. The balance in hand was £3 9s. 6½d. The Council had great faith, courage and hope, and outsiders an uncertain charity.

Those first three years, nevertheless, saw recorded in these Aeronautical Journals names now famous in aeronautical history, James Glaisher, holder of the world's height record; S. P. Langley and his remarkable steam-driven model aircraft; Percy Pilcher's gliding experiments, and those of the brothers Lilienthal in Germany and Octave Chanute in America; Hiram Maxim's aeroplane which lifted close on four tons into the air in the gay 'nineties and broke its back doing it; Lawrence Hargrave, the lone Australian experimenter who invented the box-kite, almost twenty-years before Santos Dumont, the Brazilian sportsman, flew it in France, as an aeroplane, in 1906.

To review these fifteen volumes fully would be to write much of the history of the very birth of heavier-than-air and of the teenages of lighter-than-air flight in the world, for these pages are contemporary records which must ever remain an important source of aeronautical information which is not given to the same extent elsewhere.

In these volumes Wenham, one of the Founders of the Society and the one who gave to it his first and classic lecture on the aeroplane in 1866, wrote his last paper, which was published in the same issue which announced his death, in 1908. For over forty years he had given members of the Society faith and hope in the aeroplane, and lived long enough to read of the success of the Wright Brothers. It was to these volumes that Wilbur Wright contributed the first article he ever wrote, in July 1901. In 1902 the President of the Society, Major Baden Powell, reported that "the Wright Brothers had been making wonderful progress" and in the JOURNAL for April 1904 Orville Wright contributed a first-hand account of the gliding experiments and flights at Kitty Hawk. This year, in these volumes appear the names of Moore-Brabazon British Pilot No. 1, S. F. Cody, with his man-lifting kites, following the successful experiments of Baden-Powell ten years before; G. H. Bryan who showed how to make an aeroplane stable, and, indeed, was the founder of the theory of the subject; and Eustace and Horace Short, who lectured on a pressurised balloon gondola, enabling a height of at least 11 miles to be reached; two very long-sighted Shorts.

Members of the Society during these fifteen years began travelling the world to see what other aeronautical enthusiasts were doing. Wilbur Wright came to France in 1908, and by 1911 Alec Ogilvie, Griffith Brewer and other members of the Society had become close friends of the two brothers. A dozen others from the Society went to America to take part in flying meetings there; to France and Germany and elsewhere; and the Wrights came to London in 1909 to receive the Gold Medal of the Society, the first two men in the world to receive it; and less than three months later Blériot flew the Channel; A. V. Roe, Cody, Handley Page, Sopwith, Grahame White, Blackburn, J. W. Dunne, F. K. McClean, and a whole host of others, from Europe, the United States, Canada, and obscure spots in the world were names with which to conjure, for these people were the pioneers of the flying age.

No one, who ever is urged by the desire to know how things began, can neglect the years 1897-1911 nor these records which give more account of those years by those who lived and took part in making them such astonishing years in the history of human progress, as they are.

By the offset photo-litho-process it has been possible to reproduce these early volumes so that they can become more available and more widely distributed than the originals, which have become so rare. But it should be said that these reproductions by Murray Hill may easily become rare themselves, as the interest in the early days of aeronautics becomes greater. And that is what is happening. For the farther one leaves the world for the wide open Spaces, the more earth-sick will we become.—J. L. PRITCHARD.

THE ELEMENTS OF CLASSICAL THERMODYNAMICS. *A. B. Pippard. Cambridge University Press, London, 1958. 165 pp. Illustrated. Students' edition 15s.; cloth covered 25s.*

This little book is intended for advanced students of physics; but, with the possible exception of the final chapter, it could be read with profit by any student of engineering who seeks a fairly rigorous basis for his applied thermodynamics. It has the enormous advantage that the author makes a real effort to pinpoint some of the difficulties of his subject and to clarify them.

The aims of this work having been defined in a brief introduction, the next three chapters deal in some detail with the first and second laws of thermodynamics and with reversibility. The "Miscellany of Useful Ideas" includes the derivation of Maxwell's thermodynamic relations and consideration of temperature scales and thermodynamic functions. These ideas are then applied to a number of simple systems which are well-chosen to show how general are the principles involved. After a chapter on thermodynamic inequalities and requirements for equilibrium there follow two chapters on phase equilibrium and transitions. These are both well presented but the first will be of more general interest.

It might perhaps be argued that the author has attempted to cover too much ground in too small a compass but he has produced a book which may help many students towards an understanding of this subject.

The issue of a cheaper paper-backed Students' edition, as well as the normally bound edition, is something of an innovation as far as technical publishing in this country is concerned. Any change of this sort which will help students to buy a more varied selection of text-books is to be welcomed.—H. BILLETT.

FLYING WITNESS. *Graham Wallace. Putnam, London, 1958. 260 pp. Illustrated. Index. 25s.*

Many who would enjoy reading this book will probably be put off from doing so by the subtitle: "Harry Harper and the Golden Age of Aviation." This is because Mr. Harper's name is associated in many people's minds with a long series of popular aviation books written during the past fifty years. These books have had a wide appeal mainly because they have treated their subject in a discursive and unprecise manner which apparently satisfies the casual reader but which is, at the same time, often irritating to those who are better informed about aviation.

Harry Harper was probably the first full-time air correspondent of a major newspaper. He joined the *Daily Mail* in this capacity in 1906. As a result, he watched from a privileged position and recorded the growth of aviation from its earliest practical beginnings. His writings from then up to the outbreak of the First World War in 1914 are the basis of this book. Graham Wallace has gone through his material with great care and, with the help of Mr. Charles Gibbs-Smith, has presented the story of the growth of aviation in its first formative years in an accurate and well-balanced manner. The result is something which is well worthwhile: a personal story which gives new and intimate pictures of many of the great figures of this heroic period. In fact, it combines the advantages of a well-written biography, which draws on reminiscence as well as properly documented material from the *Daily Mail*, with those of a reliable, if brief, history of aviation developments in the period 1900-1914.

The pen-pictures of Alberto Santos-Dumont, Frank Hedges Butter, C. S. Rolls, S. F. Cody, A. V. Roe, Louis Blériot, Hubert Latham, Claude Grahame-White and a number of others add a good deal to previously published accounts. They also bring out, as clearly as anything this reviewer has read before, the way in which the character and personality of these individuals accounted for, and contributed to, the parts they played in the story.

As one would expect, this book gives full details of the great *Daily Mail* prizes by means of which Lord Northcliffe made such an important contribution to the whole development of the aeroplane. The circumstances in which these prizes were offered, and sometimes won, are fully described but it is disappointing that Mr. Wallace has not been able to say something more about the careful thought which must surely have gone into selecting the particular feats chosen for encouragement by the offer of prizes of such varying sizes (between £10,000 and £250).

Although we are told a good deal about "the Chief" and his interest in aviation, one would like to know to what extent Harper played a part in advising Lord Northcliffe in the tremendously important business of the *Daily Mail* prizes. Also, it would be interesting to hear something of the factors which dictated the size of the prizes offered: the first cross-Channel flight prize was originally only £500, whereas £10,000 was put up for the first London to Manchester flight. We are at last given the answer to the old question as to why the Wrights did not try for the cross-Channel and London-Manchester prizes in 1908. They should have been able to carry them both off without much difficulty at that time when there was no effective competition. Wilbur Wright apparently believed that his aeroplanes would retain their superiority over all competitors for some years and that he could afford to postpone making his attempts for the prizes. He seems to have under-estimated the stimulating effect of his first public flights in 1908 on aviation in Europe.

Everybody interested in the history of aviation should read this book.—PETER W. BROOKS.

AERODYNAMIC COMPONENTS OF AIRCRAFT AT HIGH SPEEDS. VOLUME VII OF HIGH SPEED AERODYNAMICS AND JET PROPULSION. *A. F. Donovan and H. R. Lawrence (Editors). Oxford University Press (Princeton University Press), London, 1957. 845 pp. Illustrated. 120s.*

In the twelve-volume series on high-speed aerodynamics and jet propulsion, this 850-page book is presented in seven parts of separate authorship as follows:—

Section A. "Aerodynamics of Wings at High Speeds" by R. T. Jones and Doris Cohen.
Section B. "Aerodynamics of Bodies at High Speeds" by C. E. Brown.
Section C. "Interaction Problems" by C. Ferrari.
Section D. "Propellers for High Speed Flight" by C. B. Smith.
Section E. "Diffusers and Nozzles" by J. C. Evvard.
Section F. "Nonsteady Wing Characteristics" by I. E. Garrick.
Section G. "The Experimental Aerodynamics of Wings at Transonic and Supersonic Speeds" by C. W. Frick.

The immediate impression of this, as of other volumes in the series, is the high standard of both editing and printing, which enhance the readability of the book. It is of primary interest to designers of high-speed aircraft; the connected account of many of the theoretical ideas published during the post-war years should prove invaluable also to research students. For reference purposes there is a well-chosen bibliography of 770 works.

Sections A, C and F, occupying over three quarters of the space, are devoted to the theory of wings in steady and unsteady motion and to problems of steady interference between wings and a fuselage, tail or propeller. Equal consideration is given to the influence of compressibility at subsonic and supersonic speeds. Of the shorter contributions, Section B, which deals with the drag and lifting characteristics of slender bodies of circular and non-circular cross section, is restricted to linearised supersonic theory; unlike the rest of the volume, the discussion is not very up-to-date and, for example, ignores the area rule for drag. Sections D and E describe respectively the aerodynamics of propulsion by airscrews and jets. The final Section G is an instructive assessment of the relationships between wing theory and experiments in the speed range from compressible subsonic flow to a free-stream Mach number of about 2; available experimental data are admirably combined to justify the theme that their value lies in verifying theoretical laws and providing insight into the physical models used to formulate theory.

R. T. Jones and Doris Cohen are outstandingly qualified to review the vast field of theoretical research on lifting surfaces. From simple assumptions and with the aid of well-chosen illustrations the physical and mathematical ideas are developed side by side. There is rightly a greater emphasis on the underlying basis of a theory than on its direct application. Nevertheless, it is surprising that no mention is made of the related problem of lifting control surfaces; a little space could well have been devoted to the necessary computational processes which make or mar an elegant theory. There are useful catalogues of analytical expressions to specify an astonishing variety of two-dimensional incompressible flows and conical supersonic flows. Such fundamental ideas as similarity, compressibility, sweepback, reversed flow theorems and slender wings are clearly and readably explained; the chapters on particular solutions and general methods of solution include a realistic assessment of relative merits of the various subsonic theories. Likewise, the concepts of

subsonic and supersonic leading edges, conical flow and cancellation-of-lift procedure are well treated and lead to an interesting description of a wide range of solutions for specific plan forms in supersonic flow. Sections A and G together give a most adequate review of post-war research on wing loading.

Section C on interaction problems appears to give a full account of available methods for obtaining the lift associated with wake downwash, slipstream and wing-body interference in subsonic flow. The evaluation of wake downwash by supersonic lifting-line theory is shown to have considerable utility for rearward tail positions for which the more laborious lifting-surface integrals are of comparable accuracy. The final chapter on wing-body interference at supersonic speeds carries special authority.

The remaining Section F on transient and oscillatory flows past wings contains a description of the problems of potential theory and a review of their treatment. Of the seven sections this is probably the most difficult and therefore is primarily of value to the specialist. It is unfortunate that Multhopp's unsteady subsonic lifting-surface theory was not published in time to be included in the very complete bibliography, as this theory is the basis of standard computational forms adopted by the British aircraft industry for rigid and deforming wings.

Great advances have been made and are continuing to be made in the important fields covered by the book. Although the decision to present a comprehensive survey of the mass of accumulating papers has been well timed, it is inevitable that certain problems will have received special attention after the completion of the text. The book can be recommended to all who by theoretical means are striving towards a deeper insight into high-speed aerodynamics.—H. C. GARNER.

MISSILE ENGINEERING HANDBOOK. *C. W. Besserer. In the series Principles of Guided Missile Design. D. van Nostrand, Princeton, New Jersey, 1958. 600 pp. 109s.*

This book contains a vast amount of information likely to be of value to a missile designer, mostly presented as tables, graphs and lists of formulae. There are over 100 pages on the properties of materials; some 50 pages each on reliability and avionics; about 20 pages each on properties of the atmosphere, aerodynamics, propulsion, and space flight. The remaining 250 pages are devoted to other miscellaneous data and a gargantuan glossary. The layout of the tables is pleasing, the printing of the formulae and figures is always clear, and the grid on the graphs has a close mesh.

The author appears to have a good grasp of the subjects covered, and his glossary of common terms in missile engineering will be found very useful, especially by newcomers to the subject. He lays most emphasis on structures and engineering, as the title implies, and the aerodynamicist, for example, will not find as much data as he would like on his own special subject. Though a good deal of the tabular data is abstracted from other publications, the subjects for the tables are well-chosen, and it is a pleasure to browse through the book, culling curious items of information.

But a book like this is not for browsing; it is for reference and must be accurate. On this score the book fails badly. A cursory check revealed scores of errors. Some of these are harmless misprints: very few readers will be deluded into thinking that 27 cubic feet equal one cubic year (p. 7). But most of the errors, though still in the "misprint" category, are more serious. There are many numerical errors, even in the fundamental constants: for example, on p. 23, four successive entries giving values of powers of π are badly in error, and 1 lb./cu. in. is said to be 17·28 lb./cu. ft. on p. 10. Seeing these errors in obvious constants destroys confidence in the values given for the more abstruse ones. The same criticism applies to the formulae. Some of the misprints would be obvious to a tyro, *e.g.* "decibels$=20\log_{10}\frac{A}{A}$" on p. 189; but others might not, *e.g.* "$q=1/2\rho v^2$" on p. 43, to quote a simple example. These widespread errors seriously reduce the value of what would otherwise be an excellent reference book.—D. G. KING-HELE.

MEN AND MACHINES, A HISTORY OF D. NAPIER & SON, ENGINEERS, LTD., 1808-1958. *C. H. Wilson and W. J. Reader. Weidenfeld and Nicholson, London, 1958. 187 pp. Illustrated. 35s.*

History books usually make dry reading but the story of the great firm of D. Napier & Son, as written in its 150th year, is by no means dry. Younger readers will associate the name of Napier with the Eland turbo-prop and with the brilliant "Deltic" diesel now being introduced in high speed coastal craft and in locomotives. Older readers will recall another unusual but outstandingly successful design, the famous "Lion" aero-engine of broad-arrow configuration and the "Sabre" of the Second World War which was of even more unconventional design. Few will remember seeing Napier motor cars and lorries, but in their day they were second to none in their own class.

Napier has built up a name for precision engineering of the highest quality, perhaps less well known than it should be among the general public, due to a disinclination to publicise its products before the war. This is a very revealing book and it is extremely interesting to learn of the development of the company's work and the inspired guidance of David, James Murdoch and Montague Napier from 1808 onwards. The development of machinery for the Royal Mint for high quality printing, for gun-finishing and ultimately the manufacture of superb motor cars and aero-engines is a fascinating story.

Three generations of Napiers have left a legacy of clever, original and clear thinking in a field of engineering in which precision manufacture is of supreme importance.—A.S.C.L.

Additions to the Library

American Aces of World War II. Edward H. Sims. Macdonald, London. 1958. 318 pp. Illustrated. 18s. *To be reviewed.*

Aviation Medicine Selected Reviews. Clayton S. White, *et al.* Pergamon, London, for AGARD, 1958. 305 pp. Illustrated. 70s. *To be reviewed.*

Berechnung der Zylinderschalen, Die. Dr. Ing. A. Aas-Jakobsen. Springer-Verlag Berlin, 1958. 160 pp. Illustrated. DM 22.50 (*In German.*) Elementary beam theory can be used in the analysis of long cylindrical shells, but for medium and short cylinders it is necessary to use the theory of elasticity. This is a laborious process and a working solution is to use the theory of elasticity for the circular distribution and elementary beam theory for the longitudinal distribution. This book goes a step farther in introducing a hypothetical shell, for which the solution can be calculated and tabulated, and in which the boundary conditions agree with those of

the actual shell. Tables of constants are included as an aid to the resulting simplified, yet accurate, analysis.

Civil Air Regulations and Flight Standards for Pilots. Aero Publishers, Los Angeles. 20th Edition. 2.25 dollars. **Civil Air Regulations for Mechanics.** Aero Publishers. 1958. 14th Edition. 2.50 dollars. The Civil Aeronautics Administration of America issues regulations for the control of aircraft which are a full-time occupation to file, let alone become familiar with. Aero Publishers perform an invaluable service in extracting those that are necessary to the various grades connected with aviation and publishing them in separate booklets, at reasonable prices and with explanatory material added. Other chapters give typical examination questions, recommended further reading material, a list of regional offices and so on.

Congrès International de Mécanique Appliquée IXe. Actes. Tome IV. Université de Bruxelles, 1957. 504 pp. Illustrated. This, the latest published volume of the Congress, contains material on boundary layer theory, hydrodynamics lubrication, porosity and experimental techniques. A little more than a half of the 43 papers are in English, the rest are in French, and the list of authors includes many names well known in the United States, Great Britain, France, Germany and the U.S.S.R. in these various fields of applied mechanics.

Flying Witness. Graham Wallace. Putnam, London, 1958. 272 pp. Illustrated. 25s. *Reviewed in this issue.*

Heat Bibliography 1955-56 Parts I and II. Mechanical Engineering Research Laboratory, East Kilbride. D.S.I.R. 631 pp. (both parts). The bibliography is divided into 49 subject headings and these, again, are sometimes subdivided (in the case of "Chemical and Physical References to Particular Substances," 21 sub-headings). It would appear to be exhaustive and a two-year time-lag is understandable and excusable when one sees the ground covered.

Introduction to the Design of Servomechanisms. J. L. Bower and P. M. Schultheiss. John Wiley, New York (Chapman and Hall, London), 1958. 510 pp. Illustrated. 104s. *To be reviewed.*

Jet Stream. R. Lee. Smithsonian Institution. 1958. Washington. Illustrated. 10 cents. A reprint of an article from *The Roundel*, the Journal of the R.C.A.F. The subject is treated from the meteorological standpoint.

Link between Schools and Industry, The—A Report on a Conference. Gloucestershire Industrial Education Council, 1958. 106 pp. 5s. The G.I.E.C. is formed by the firms and education authorities in the West country and the conference was held in October 1958. The first day was devoted to "What Gloucestershire Schools have to offer Industry" and the second to "The Implications of New Technological Developments." Aeronautics plays a large part in both subjects.

Men and Machines (Napier Story). C. H. Wilson and W. J. Reader. Weidenfeld and Nicholson, London, 1958. 187 pp. Illustrated. 35s. *Reviewed in this issue.*

Plasma in a Magnetic Field, The. R. K. N. Landshoff (*Editor*). Stanford University Press, California (Oxford University Press, London), 1959. 130 pp. Illustrated. 36s. Contains the proceedings of the second Symposium on Magnetohydrodynamics, sponsored by the Missile Systems Division of Lockheeds and held at Palo Alto in December 1957. (The proceedings of the first symposium were reviewed in the JOURNAL for April 1958 (p. 311).) The present volume is concerned with plasmas, rather than with liquid metals, and is in three sections—Kinetic Theory, Confinement and Instabilities of a Plasma, High Speed Fluid Dynamics.

Problems of Lift and Stability in Aeroplane Design. F. Handley Page. Proceedings of the Royal Philosophical Society of Glasgow Vol. LX 1931-2, pp. 34-53. A paper dealing largely with the slotted wing.

References on Atomic, Photon and Ion Propulsion of Aircraft, the Shielding of Aircraft Nuclear Reactors, the Medical Hazards of Atomic-Powered Aircraft and the Effect of Atomic Radiation on Aircraft Materials and Components. A. T. E. Bray (*Compiler*). R. A. E. Library Bibliography No. 195, 1957. Ministry of Supply. Unpublished. 35 pp. Compiled by the Deputy Librarian at R.A.E. from eight different sources. It ranges from 1945 to 1957.

Sky Smuggler. Geoffrey Williamson. Robert Hale, London, 1958. 176 pp. Illustrated. 16s. An interesting, factual account of the development of Customs-evasion techniques brought about during the phenomenal increase of air traffic in the past fifty years. The counter-measures used by Preventive Officers to combat these techniques and to prevent loss of revenue—a large part of this is from diamond smuggling—are described in so far as this is advisable, and some indications are given of the training for recruits to the Customs service.

Specification for Manufacturers' Technical Data. A. T. A. Specification No. 100. Air Transport Assoc. of America. Washington. The requirements of the scheduled airline industry for technical manuals which will be required for future commercial aircraft are outlined in detail.

Studies of Noise Characteristics of the Comet 4 Jet Airliner and of Large Conventional Propeller-Driven Airliners. Bolt Beranek and Newman, Port of New York Authority, 1958. Approximately 240 pp. Illustrated. **Studies of Noise Characteristics of the Boeing 707-120 Jet Air Liner and of Large Conventional Propeller-Driven Airliners.** Bolt Beranek and Newman, Port of New York Authority, 1958. Approximately 220 pp. Illustrated. These reports of the recent and much-discussed jet noise tests at New York International Airport contain, not only the absolute results, but explanations of the physical measurement of sound and human reaction to it. Methods of test are fully described.

Tables for Bivariate Osculatory Interpolation over a Cartesian Grid. H. E. Salzer and Genevieve M. Kimbro. Convair-Astronautics, San Diego, 1958, 40 pp.

Tables of Thermodynamic Functions of Air. A. S. Predvoditelev. Cleaver-Hume, New York, 1958. 301 pp. Illustrated. 63s. This volume forms one of a series of tables covering the range 1000° to 20,000°K. The following properties are each listed to four significant places: internal energy, enthalpy, entropy, specific heat at constant volume and at constant pressure, the ratio of specific heats, velocity of sound, density, molecular weight, and 13 molar fractions of the constituents of air.

Ten Steps into Space. Franklin Institute (Monograph No. 6). Philadelphia, 1958. 202 pp. Illustrated. $4. The ten steps into space are ten papers by authoritative American writers. They are Willy Ley, Kurt Stehling (Head of the Vanguard Rocket Division of N.R.L.), H. W. Ritchey (Vice-President of Thiokol Chemical), S. F. Singer (University of Maryland Physics Department), Paul Herget (Staff Head, Vanguard Computer Centre), Gerhard Heller (of Redstone Arsenal), K. A. Ehricke (of Convair-Astronautics), J. I. F. King (General Electric Aero Sciences Laboratories), David G. Simons (a Lieutenant-Colonel at Holloman Air Force Base) and I. M. Levitt (Director of the Fels Planetarium of the Franklin Institute). This monograph covers considerable ground and the Institute has done a service by producing a volume at such low cost.

Theory and Design of Magnetic Amplifiers, The. E. H. Frost-Smith. Chapman and Hall, London, 1958. 487 pp. Illustrated. 75s. *To be reviewed.*

Reports

AERODYNAMICS

BOUNDARY LAYER—*see also* COMPRESSIBLE FLOW

Some details of the quintic profile for use in the Pohlhausen-type of boundary-layer calculation. N. Curle. C.P. 391 1958.
The Pohlhausen method for approximate calculation of the laminar boundary layer uses a quartic one-parameter family of velocity profiles. The general theory is developed for a quintic profile, satisfying an additional boundary condition at the wall. A detailed analysis is given for a linearly retarded main-stream. —(1.1.1.1).

Experiments on the use of suction through perforated strips for maintaining laminar flow: transition and drag measurements. N. Gregory and W. S. Walker. R. & M. 3083. 1958.
Wind-tunnel tests are described in which suction is applied at perforated strips, as an alternative to porous strips or slots, to maintain a laminar boundary layer. A test was first made on a single row of perforations on a cambered plate, as a preliminary to the main tests which were performed on strips of multiple rows of perforations drilled through the surface of a low-drag-type aerofoil 13 per cent thick and of 5 ft. chord.—(1.1.5.1)

A low-speed experimental investigation of the effect of a sand-paper type of roughness on boundary layer transition. A. E. von Doenhoff and E. A. Horton. N.A.C.A. Report 1349 (*supersedes N.A.C.A.* 3858). 1958.—(1.1.2.1).

On possible similarity solutions for three-dimensional incompressible laminar boundary-layer flows over developable surfaces and with proportional mainstream velocity components. A. G. Hansen. N.A.C.A. T.M. 1437. *September* 1958.
Requirements for the existence of similarity solutions are obtained for boundary layer equations expressed in orthogonal co-ordinates. Permissible forms of main stream velocity components, the square of differential of arc length on the surface, and the similarity parameter are found. A basic class of surfaces is found from which all other permissible surfaces may be obtained.—(1.1.1.1).

The turbulent boundary layer on a rough curvilinear surface. V. F. Droblenkov. N.A.C.A. T.M. 1440. *September* 1958.
A method has been derived for the calculation of the turbulent boundary layer skin-friction drag on a flat plate or a curvilinear surface with a pressure gradient with or without distributed roughness. The method has been checked by comparing the calculated with the measured drag of an airfoil, smooth and with each of two grades of carborundum on the surface.—(1.1.3).

Similar solutions for the compressible boundary layer on a yawed cylinder with transpiration cooling. I. E. Beckwith. N.A.C.A. T.N. 4345. *September* 1958.
Heat-transfer and skin-friction parameters obtained from exact solutions to the laminar compressible boundary layer equations for infinite cylinders in yaw are presented. The effects of transpiration cooling, Prandtl number, pressure gradient, wall temperature, and viscosity relation were investigated.—(1.1.1.4 × 1.9.1).

Theoretical distribution of laminar-boundary-layer thickness, boundary-layer Reynolds number and stability limit, and roughness Reynolds number for a sphere and disk in incompressible flow. N. Tetervin. N.A.C.A. T.N. 4350. *Sept.* 1958.—(1.1.1.1).

Simplified method for determination of critical height of distributed roughness particles for boundary layer transition at Mach numbers from 0 to 5. A. L. Braslow and E. C. Knox. N.A.C.A. T.N. 4363. *September* 1958.
A single equation is derived which relates the roughness height to a Reynolds number based on the roughness height and on local flow conditions at the height of the roughness, and charts are presented from which the critical roughness height can be easily obtained for Mach numbers from 0 to 5. The method has been applied to various types of configurations in several wind-tunnel investigations at Mach numbers up to 4.—(1.1.2).

An investigation of supersonic turbulent boundary layers on slender bodies of revolution in free flight by use of a Mach-Zehnder interferometer and shadowgraphs. A. Seiff and B. J. Short. N.A.C.A. T.N. 4364. *September* 1958.
The models are slender pointed bodies of revolution gun-launched in free flight at Mach numbers of 3·2 and 3·6 with length Reynolds numbers of 10 million and 25 million. Fluctuations of air density in these boundary layers are observed. The mean density distributions are compared with those given by the Crocco equation, and the mean heat transfer is computed from an energy balance and compared with that given by the modified Reynolds analogy.—(1.1.3.4 × 1.9.1 × 1.12.2).

Large-scale wind tunnel tests of an airplane model with an unswept, aspect-ratio-10 wing, two propellers, and area-suction flaps. J. A. Weiberg et al. N.A.C.A. T.N. 4365. *Sept.* 1958.
An investigation was made to determine the effects of a propeller slipstream on the lifts obtainable and the flow requirements for suction applied to a porous area on a trailing-edge flap on a large-scale model of an aeroplane having a high aspect ratio, thick, straight wing.—(1.1.5.1 × 1.3.4 × 1.10.2.2).

Some numerical solutions of similarity equations for three-dimensional laminar incompressible boundary layer flows. P. L. Yohner and A. G. Hansen. N.A.C.A. T.N. 4370. *September* 1958.
Numerical solutions are presented for two classes of similarity equations corresponding to a range of three-dimensional boundary layer flows. Equations for limiting-flow deflection and for the calculation of boundary layer streamlines are also given. —(1.1.1.1).

Approximate solutions of a class of similarity equations for three dimensional, laminar, incompressible boundary layer flows. A. G. Hansen and H. Z. Herzig. N.A.C.A. T.N. 4375. *September* 1958.
An analysis is presented for obtaining approximate solutions of the similarity equations for three dimensional laminar boundary layer flows over a flat surface under main-flow stream lines that are translates and representable as infinite series expansions. For the particular case of stream line shapes described by a power of the distance along the surface from the leading edge, relatively simple expressions are obtained for flow deflection at the bounding surface, limiting stream line shape, and shear stress at the surface.—(1.1.1.1).

Approximate method for calculation of laminar boundary layer with heat transfer on a cone at large angle of attack in supersonic flow. W. E. Brunk. N.A.C.A. T.N. 4380. *September* 1958.
By the use of an integral technique, the laminar boundary layer equations are reduced on the windward generator of the plane of symmetry to a set of simultaneous algebraic equations. The method enables the skin-friction coefficients and Stanton number to be calculated in a much shorter time than was needed to obtain exact numerical solutions from the boundary layer equations.—(1.1.1.4 × 1.9.1).

Analysis of turbulent flow and heat transfer in non-circular passages. R. G. Deissler and M. F. Taylor. N.A.C.A. T.N. 4384. *September* 1958.
Previous work on turbulent heat transfer and flow in tubes was generalised and applied to flow in non-circular passages of equilateral triangular and square cross section. Expressions for eddy diffusivity that had been verified for flow and heat transfer in tubes were assumed to apply in general along lines normal to a wall. Velocity distributions, wall shear-stress distributions, friction factors, wall heat-transfer and temperature distributions, and average heat-transfer coefficients were calculated. The peripheral temperature variation was assumed small compared with the variation of temperature across the passage.—(1.1.3.1 × 34.3).

Effects of nose angle and Mach number on transition on cones at supersonic speeds. K. R. Czarnecki and M. W. Jackson. N.A.C.A. T.N. 4388. *September* 1958.
An investigation has been made to determine the transition characteristics of a group of smooth, sharp-nosed cones varying from 10° to 60° in included apex angle over a Mach number range from 1·61 to 2·20.—(1.1.2.4).

*The unit Reynolds number as a parameter in boundary layer stability. J. D. Whitfield and J. L. Potter. A.S.T.I.A. A.D.-*202731.
A possible basis for the general, experimentally demonstrated, upward trend of Reynolds number of transition with increasing free-stream unit Reynolds number is sought in stability theory.

To eliminate effects caused by leading edge shock waves, the analysis considers subsonic flow. The only variables allowed are the unit Reynolds number and accompanying changes in frequency and energy of fluctuations which are believed to be affected by the unit Reynolds number.—(1.1.2.2).

Canadian research in aerodynamic noise. B. Etkin and H. S. Ribner. U.T.I.A. Review 13. *July* 1958.
Specific experimental and/or theoretical investigations include: Aeolian Tones; Boundary Layer Noise (rigid wall and flexible wall); Effects of Boundary Layers and Noise on Aircraft Structures; Distribution of Noise Sources Along a Jet; Ground Run-up Mufflers; Transmission of Sound from, and Acoustic Energy Flow in, a Moving Medium; Sound Generated by Interaction of a Vortex with a Shock Wave.—(1.1×5.6×33.1.2).

*Das Verhalten der drei-dimensionalen, laminaren Grenzschicht-strömung bei zunehmenden Anstellwinkeln. J. A. Zaaf. N.L.L. T.N. F.*215. *April* 1958. (*In German*).—(1.1.1.1).

Methode voor kwalitatief grenslaagonderzoek met behulp van gloeidraden zonder beinvloeding der stroming. P. C. A. Malotaux et al. V.T.H. Report 45. *May* 1951. (*In Dutch*).
A method is described to determine the local character of the boundary layer flow past a wing surface. This character can be reduced from the conduct of hot wires, which are not placed in the boundary layer flow, but below static pressure orifices in the wing surface. The flow remaining undisturbed, the method can be combined with measurements of the chordwise pressure distribution and wake measurements of the profile drag.—(1.1.2.1×1.12.6.3).

Simultaneous effects of pressure gradient and transverse curvature on the boundary layer along slender bodies of revolution. M. Yasuhara. Aero. Res. Inst., Tokyo. August 1958.
Calculations of the effects of pressure gradient and transverse curvature on the boundary layer along slender bodies of revolution are made for allowable body shapes by the series expansion method. Two methods of calculation are presented: the perturbation expansion of flow quantities from the uniform state, and that from the stagnation state. As an example of the first method, the boundary layer flow along a slender paraboloid of revolution is calculated.—(1.1.1).

COMPRESSIBLE FLOW—*see also* INTERNAL FLOW
THERMO-AERODYNAMICS

A note on the interpretation of base pressure measurements in supersonic flows. R. C. Hastings. C.P. 409. 1958.—(1.2.3).

On flow of electrically conducting fluids over a flat plate in the presence of a transverse magnetic field. V. J. Rossow. N.A.C.A. Report 1358. 1958. (*Supersedes N.A.C.A. T.N.* 3971.)
Several basic boundary layer solutions for the velocity and temperature profiles are found for flow of electrically conducting fluid over a flat plate in the presence of a transverse magnetic field.—(1.2.4.1×1.9.1).

Hypersonic viscous flow over slender cones. L. Talbot et al. N.A.C.A. T.N. 4327. *September* 1958.
Viscous self-induced pressures on 3°-semivertex-angle cones were measured over the range $3{\cdot}7 <$ free-stream Mach number $< 5{\cdot}8$ and $0{\cdot}5 <$ viscous-interaction parameter < 2.3. A new method for calculating self-induced pressures is presented which takes into account the interaction between boundary layer growth and the inviscid-flow field at the outer edge of the boundary layer.—(1.2.3×1.1.1.4).

Tables and graphs of normal-shock parameters at hypersonic Mach numbers and selected altitudes. P. W. Huber. N.A.C.A. T.N. 4352. *September* 1958.
Tables and graphs of normal shock parameters corresponding to six selected altitudes below 300,000 ft. and for temperatures behind the shock from 2,000°K to 11,000°K are presented for real air in thermal and chemical equilibrium. The altitude data and real air thermodynamic data used in the computations represent reliable values for application to aerodynamic flight in the atmosphere. Values of the normal shock Mach numbers, flight velocity, enthalpy behind the shock, and of pressure, density, temperature, and velocity of sound ratios are presented to show variations with temperature behind the shock, flight Mach number, and altitude.—(1.2.3.2×1.9).

A study of several theoretical methods for computing the zero-lift wave drag of a family of open-nosed bodies of revolution in the Mach number range of 2·0 *to* 4·0. *L. L. Presley and E. A. Mossman. N.A.C.A. TN.* 4368. *September* 1958.
Computations made by six approximate methods, first- and second-order perturbation theory, generalised shock expansion theory, second-order shock expansion theory, tangent wedge theory, and impact theory, are compared to the values given by the method of charateristics.—(1.2.3.2).

Comparison of shock-expansion theory with experiment for the lift, drag, and pitching-moment characteristics of two wing-body combinations at $M = 5{\cdot}0$. *R. C. Savin. N.A.C.A. T.N.* 4385. *September* 1958.
Two wing-body combinations were tested in the Ames 10×14 inch supersonic wind tunnel. Lift, drag, and pitching-moment characteristics were determined at a Mach number of 5·0 and angles of attack up to 9°. Theoretical results obtained with the aid of the generalised shock expansion method were compared with experiment.—(1.2.3).

Free-flight investigation to determine the drag of flat- and vee-windshield canopies on a parabolic fuselage with and without transonic indentation between Mach numbers of 0·75 *and* 1·35. *W. L. Kouyoumjian and S. Hoffman. N.A.C.A. T.N.* 4405. *September* 1958.
The flat windshield canopies investigated had overall fineness ratios of about 7·00 and 4.50. The vee-windshield canopies had fineness ratios of about 7·00. Models of all the canopy-fuselage configurations with transonic-area-rule indentations were also tested.—(1.2.2).

Theoretical studies of unsteady transonic flow. Part I: Linearization of the equations of motion. M. T. Landahl. F.F.A. Report 77. 1958.—(1.2.2.1).

CONTROL SURFACES—*see* BOUNDARY LAYER

FLUID DYNAMICS

Velocity distributions and shapes for free streamline bodies having wedge-shaped noses. J. Pierce et al. Douglas Report ES 29123. *August* 1958.—(1.4×1.10.1.1).

INTERNAL FLOW—*see also* TESTING AND INSTRUMENTS

The development of a variable-Mach-number effuser. J. B. McGarry. R. & M. 3097. 1958.
A series of tests was undertaken on a simple, two dimensional, variable Mach number effuser, or nozzle, designed for the range of supersonic flows up to a Mach number of 3·0. The performance of the nozzle was assessed from the magnitude of the percentage variation in its exit Mach number distribution. Studies of the effect on the performance of alterations to the position of the nozzle block pivots and other geometrical features were made. On the basis of these studies a final build of nozzle was developed which produced flow of a uniformity sufficient for intake and engine model testing over the Mach number range from 1·5 to 3·0.—(1.5.1).

Application of the method of co-ordinate perturbation to unsteady duct flow. S. C. Himmel. N.A.C.A. T.M. 1439. *September* 1958.
Perturbation series solutions are obtained for the unsteady flow of a compressible fluid in ducts of variable cross section. Among the problems treated is that of the interaction of a disturbance and a shock wave in a diffuser flow. The flow field behind a shock wave moving on a prescribed path in the x, t-plane is also developed as a perturbation series.—(1.5.1×1.2.3.1).

Experimental investigation of axial and normal force characteristics of skewed nozzles. D. J. Carter and A. R. Vick. N.A.C.A. T.N. 4336. *September* 1958.
An investigation of axial and normal force characteristics of skewed nozzles and ejectors with skewed shrouds, all discharging into quiescent air, has been conducted. Simple skewed nozzles of varying geometry and ejectors consisting of either an axisymmetric or skewed primary nozzle shrouded by a secondary skewed nozzle were tested with a cold jet at jet total pressure ratios up to approximately 6·5. For ejectors, diameter ratios varied from 1·05 to 1·45 and spacing ratio from 0·5 to 2·87.—(1.5.1×27.1).

Use of the Coanda effect for jet deflection and vertical lift with multiple-flat-plate and curved-plate deflection surfaces. U. H. von Glahn. N.A.C.A. T.N. 4377. *September* 1958.
Deflectors consisting of two, three, six and nine flat plates and

curved plates, all using the Coanda effect for achieving jet deflection and lift, were tested in quiescent air.—(1.5.1.2×1.8.2).

Investigation of boiling burnout and flow stability for water flowing in tubes. W. H. Lowdermilk et al. N.A.C.A. T.N. 4382. *September* 1958.
The effects of flow restriction and compressible volume, located ahead of the test section, on flow stability and burnout heat flux were surveyed experimentally with water flowing in tubes. Correlations of the data are presented for low- and high-quality burnout regimes.—(1.5.1.1×1.9.1).

LOADS—*see also* STABILITY AND CONTROL

An approach to the problem of estimating severe and repeated gust loads for missile operations. H. Press and R. Steiner. N.A.C.A. T.N. 4332. *September* 1958.
An analysis of available information on atmospheric turbulence is presented in order to arrive at a simple description of the atmospheric turbulence environment appropriate for missile operations. This simplified description is used to derive methods of estimating severe and repeated gust loads in missile operations in terms of missile response characteristics and operating parameters for given probabilities of exceedance.—(1.6.3×25.2).

Measurements of aerodynamic forces and moments at subsonic speeds on a simplified T-tail oscillating in yaw about the fin midchord. S. A. Clevenson and S. A. Leadbetter. N.A.C.A. T.N. 4402. *September* 1958.
Coefficients which define rolling moment of the horizontal stabiliser alone and rolling moment, yawing moment, and side force of the complete T-tail are shown.—(1.6.3×2).

STABILITY AND CONTROL—*see also* INTERNAL FLOW

Measurements of the motions of a large swept-wing airplane in rough air. R. H. Rhyne. N.A.C.A. T.N. 4310. *September* 1958.
The results of a flight investigation of the angular and linear motions of a large swept-wing aeroplane in rough air for altitudes of 5,000 and 35,000 ft. are summarised in the form of sample time histories, power spectra, root-mean-square values, and probability distributions.—(1.8.0.1×1.6.3×24).

THERMO-AERODYNAMICS—*see also* BOUNDARY LAYER
COMPRESSIBLE FLOW
INTERNAL FLOW

A survey and correlation of data on heat transfer by forced convection at supersonic speeds. R. J. Monaghan. R. & M. 3033. 1958.
The main aim was to seek possible explanations for the occasional apparent inconsistencies between wind tunnel results from different sources, between wind tunnel and flight results and between either type of experimental results and the predictions of theory. The main topics covered are kinetic temperature rise, heat-transfer coefficients and transition from laminar to turbulent flow. Conclusions are reached about the reliability of the data for design purposes and suggestions are made on the most useful fields of study for experimental work.—(1.9.1).

Effect of some external crosswise stiffeners on the heat transfer and pressure distribution on a flat plate at Mach numbers of 0·77, 1·39 *and* 1·98. *H. S. Carter. N.A.C.A. T.N.* 4333. *Sept.* 1958.
The investigation was made in a free jet for Reynolds numbers from 3×10^6 to 14×10^6, based on a length of one foot.—(1.9.1).

Slip-flow heat transfer from cylinders in subsonic airstreams. L. V. Baldwin. N.A.C.A. T.N. 4369. *September* 1958.
Heat transfer coefficients for normal cylinders in air were measured for Mach numbers 0·05 to 0·80, Reynolds numbers one to 75, and Knudsen numbers 0·009 to 0·077 at air temperatures from 0° to 280°F and wire temperatures from 34° to 620°F.—(1.9.1×1.12.6.3).

Analytical and experimental investigation of temperature recovery factors for fully developed flow of air in a tube. R. G. Deissler et al. N.A.C.A. T.N. 4376. *September* 1958.
The analysis was made for turbulent and laminar flow. The effect of wall temperature gradient along the tube was investigated. Recovery factors were obtained experimentally for a range of Reynolds numbers from 630 to 30,000. Additional previously unpublished data are presented for Reynolds numbers up to 650,000.—(1.9.1×1.2.1).

Preliminary heat-transfer studies on two bodies of revolution at angle of attack at a Mach number of 3·12. *N. Sands and J. R. Jack. N.A.C.A. T.N.* 4378. *September* 1958.
Heat transfer rates were studied on a cone cylinder and a parabolic nosed cylinder at angles of attack up to 18°. Data were obtained for the initially cooled models at Reynolds numbers of $6\cdot8\times10^6$ and $12\cdot0\times10^6$ based on model length.—(1.9.1).

TESTING AND INSTRUMENTS—*see also* BOUNDARY LAYER
THERMO-AERODYNAMICS
METEOROLOGY

The theoretical performance of shock tubes designed to produce high shock speeds. B. D. Henshall. C.P. 407. 1958.
Ideal-gas calculations are made of the performance of a double diaphragm shock tube using hydrogen as the driver gas, argon in the intermediate section and air as the final driven gas. A comparison is made of the performance of this shock tube with that of a single diaphragm shock tube using a hot hydrogen or combustion driver.—(1.12.1.3).

Static response of a hemispherical-headed yawmeter at high subsonic and transonic speeds. P. G. Hutton. C.P. 401. 1958.
Details are given of the static calibration of a hemispherical-headed differential pressure yawmeter, in the Mach number range from 0·6 to 1·2; the instrument has a central pitot pressure hole and two pairs of holes in perpendicular planes for flow direction measurement.—(1.12.5).

Pressure probes selected for three-dimensional flow measurement. D. W. Bryer et al. R. & M. 3037. 1958.
Seven pressure probes have been tested in a uniform stream to ascertain the best types for measuring velocity and flow direction. Methods of calibration are discussed together with the effects of wind speed, flow direction and turbulence on the calibration factors. The performance of three of the probes in the turbulent boundary layer of a flat plate is analysed and their accuracies compared when they are used to estimate displacement and momentum thicknesses.—(1.12.5).

The development of slotted working-section liners for transonic operation of the R.A.E. Bedford 3 *ft. wind tunnel. E. P. Sutton. R. & M.* 3085. 1958.—(1.12.1.2).

Lag in pressure systems at extremely low pressures. W. T. Davis. N.A.C.A. T.N. 4334. *September* 1958.
A theoretical formula for determining lags in pressure-measuring systems at all pressures, including extremely low pressures where molecular flow occurs, is derived and shown to be accurate to within 10 per cent for pressures down to approximately 0·2 millimeter of mercury (0·556 lb./sq. ft.) for nearly linear pressure changes.—(1.12.5×1.5.1).

A cooled-gas pyrometer for use in high-temperature gas streams. L. N. Krause et al. N.A.C.A. T.N. 4383. *September* 1958.
An immersion-type pyrometer is described which utilises the controlled cooling of a continuously aspirated sample of the gas whose temperature is to be measured. Experimental data were obtained with the cooled-gas pyrometer in a 2000° to 4000° R gas stream.—(1.12×34.3).

INSTRUMENTS AND EQUIPMENT

See also STRUCTURES—LOADS

The compressive instability of a hydraulic jack. E. Kosko. U.T.I.A. Report 55. *August* 1958.
The buckling of a hydraulic jack is analysed on the basis of a new concept, that of partly overlapping stiffnesses, believed to be more rational than previous approaches. General formulae are derived and numerical results are presented in the form of design charts. The effects of inelastic material behaviour, of transverse loads and of initial imperfections are also considered. A similar method for undercarriage shock-absorber struts is indicated.—(18.2×33.2.3).

MATERIALS

Effect of precipitate particles on creep of aluminum-copper alloys during age hardening. E. E. Underwood et al. N.A.C.A. T.N. 4372. *September* 1958.
Spherical or platelike precipitates were prepared in aluminium alloys with 1 to 4 weight per cent copper. The effects of controlled sizes and distributions of particles were determined by creep, tensile, and hardness measurements, by quantitative metallographic evaluation of the particle characteristics, and by X-ray and electron-microscope examinations.—(21.2.2).

The theory of diffusion in strained systems. L. A. Girifalco and H. H. Grimes. N.A.C.A. T.N. 4408. *September* 1958.
A general theory of solid state diffusion in strained systems is developed on a molecular kinetic basis. The theory predicts that for simple strains the diffusion coefficient is an exponential function of the lattice parameter and that the rate of change of the diffusion coefficient with strain is linearly related to the inter-atomic forces. It is shown that for plastic flow the diffusion coefficient is a linear function of strain rate.—(21.1 × 33.2.1).

Glide path effects and work hardening in aluminium single crystals. N. A. McKinnon. A.R.L. Report MET. 29. *March* 1958.
Metallographic and X-ray techniques have been used to study the influence of length of glide path on the work hardening of aluminium single crystals oriented within the basic stereographic triangle.—(21.2.2).

The source of the nitrogen impurity in electrodeposited chromium. N. Ryan and E. J. Lumley. A.R.L. Report MET. 30. *August* 1958.—(21.2.2).

Corrosion sèche et protection des alliages réfractaires Ni-Cr 80/20. *M. Mathieu. AGARD Report* 159. *November* 1957. (*In French.*)
From metallurgical considerations, the failure of blades made from forged heat resistant alloys of the Ni-Cr 80/20 type is investigated. A surface treatment is suggested for the protection of such alloys against crack corrosion.—(21.2.2).

On the fracture of metals. M. Uemura. Aero. Res. Inst., Tokyo. Report 334. *August* 1958.
A phenomenological fracture hypothesis for polycrystalline materials is presented. Experimental data is used to verify the hypothesis.—(21.1).

METEOROLOGY

See also AERODYNAMICS—STABILITY AND CONTROL

Some thermal aspects of the design of heated probes for measuring cloud water content. D. C. Baxter. N.A.E. Report L.R.-72A. August 1958.
The performance of the heated wire is analysed on a theoretical basis, and the effect of various operating parameters illustrated. The transient and frequency responses are discussed and the fast response compared with most other instruments demonstrated. The probable error in recorded value of water content is calculated for a typical case. Other forms of thermal instrument are compared with the heated wire.—(24 × 1.12.6.3).

MISSILES

See also AERODYNAMICS—LOADS

Relative motion in the terminal phase of interception of a satellite or a ballistic missile. R. A. Hord. N.A.C.A. T.N. 4399. *September* 1958.
Two types of interception are discussed mathematically and a numerical example is worked out for each type.—(25.1).

POWER PLANTS

See also AERODYNAMICS—INTERNAL FLOW

Atmosphere breathing engines in astronautics. S. W. Greenwood and D. S. Carton. C.o.A. Note 88. *October* 1958.
Part I considers the possibilities and problems involved in using ram-jets as a power source for one of the stages of a satellite launching vehicle or similar project. Various trajectories are considered. A reassessment of projects that have been suggested elsewhere is included. Part II examines the possibility of using forms of ram-jet in the atmosphere of other planets. Because there is insufficient knowledge of these atmospheres, a study has been made to determine the approximate performance of a chemical ram-jet in atmospheres of Methane, Ammonia, Hydrogen and Carbon Dioxide at Mach 3.—(27.4 × 8).

FATIGUE

Thermal fatigue of ductile materials: I—Effect of variations in the temperature cycle on the thermal-fatigue life of S-816 and Inconel 550. *N.A.C.A. T.N.* 4160. *II—Effect of cyclic thermal stressing on the stress-rupture life and ductility of S-816 and Inconel* 550. *F. J. Clauss and J. W. Freeman. N.A.C.A. T.N.* 4165. *September* 1958.—(31.2.2.7.1.8).

An investigation of the effects of atmospheric corrosion on the fatigue life of aluminum alloys. H. A. Leybold et al. N.A.C.A. T.N. 4331. *September* 1958.
Fatigue tests were conducted on 100 vibrating cantilever sheet specimens by applying 4,000 cycles of load in a 10 minute period each working day while the specimens were subjected to atmospheric conditions over a period of several months. Specimens of 2024-T3 and 7075-T6 aluminium alloys in both the bare and clad forms were tested. For comparison, 96 specimens were tested indoors.—(31.2.2.3.1.7).

STRUCTURES

LOADS—*see also* AERODYNAMICS—BOUNDARY LAYER

Measurements of ground reaction forces and vertical center of gravity accelerations of a bomber airplane taxiing over obstacles. J. M. McKay et al. N.A.C.A. T.N. 440. *September* 1958.
Results are presented of the effects of ground speed and the widths and heights of the obstacles on the vertical and rearward drag ground reaction forces, the vertical acceleration at the centre of gravity of the aeroplane, the shock-strut displacement, and the dynamic response of the upper mass of the aeroplane structure.—(33.1).

Low tire friction ond cornering forces on a wet surface. E. N. Harrin. N.A.C.A. T.N. 4406. *September* 1958.
Typical tyre behaviour on wet runways was investigated. A specially constructed tyre treadmill served as a tyre test vehicle whereas force measurements were made by means of a strain-gauge balance.—(33.1 × 18).

THEORY AND ANALYSIS—*see also* INSTRUMENTS AND EQUIPMENT MATERIALS

Thermal stresses in thin cylindrical shells stiffened by plane bulkheads for arbitrary temperature distributions. D. J. Johns. C.o.A. Note 83. *July* 1958.
A study of the thermal stresses resulting near the joint of a cylinder and internal bulkhead due to arbitrary temperature distributions in the configuration and to the consequent compatibility forces and moments at the joint.—(33.2.3.3.9).

Thermal stresses in a box structure. B. M. Lempriere. C.o.A. Note 84. *July* 1958.
An interim note of an analysis, using an energy method, of the thermal stresses in a finite length box structure resulting from uniform skin heating. The solution depends upon an eighth order differential equation with constant coefficients. Numerical solutions are given for comparison with existing and projected experiments.—(33.2.3.0.9).

Heat transfer and thermal stresses in sandwich panels. R. T. Swann. N.A.C.A. T.N. 4349. *September* 1958.
Calculated maximum temperature differences between faces and calculated thermal stresses are presented for sandwich panels with a prescribed linear rate of temperature rise at one face and with the other face insulated. Effects of conduction and radiation are included.—(33.2.4.6.9).

Analysis of the creep behavior of a square plate loaded in edge compression. H. G. McComb. N.A.C.A. T.N. 4398. *Sept.* 1958.
A theoretical analysis of a simply supported plate subject to creep. The plate is assumed to be made of a material which obeys a non-linear creep law. An approximate solution is made using a previously published variational theorem for creep.—(33.2.4.5.1).

Tests of ring-stiffened circular cylinders subjected to a transverse shear load. J. P. Peterson and R. G. Updegraff. N.A.C.A. T.N. 4403. *September* 1958.
Thirty-four circular cylinders stiffened by heavy rings were loaded to failure in combined bending and shear with a transverse shear load. The results are presented in the form of an interaction curve which is applicable to the design of ring stiffened cylinders that fail as a result of local buckling.—(33.2.4.3.4).

THERMODYNAMICS

See AERODYNAMICS—BOUNDARY LAYER
TESTING AND INSTRUMENTS

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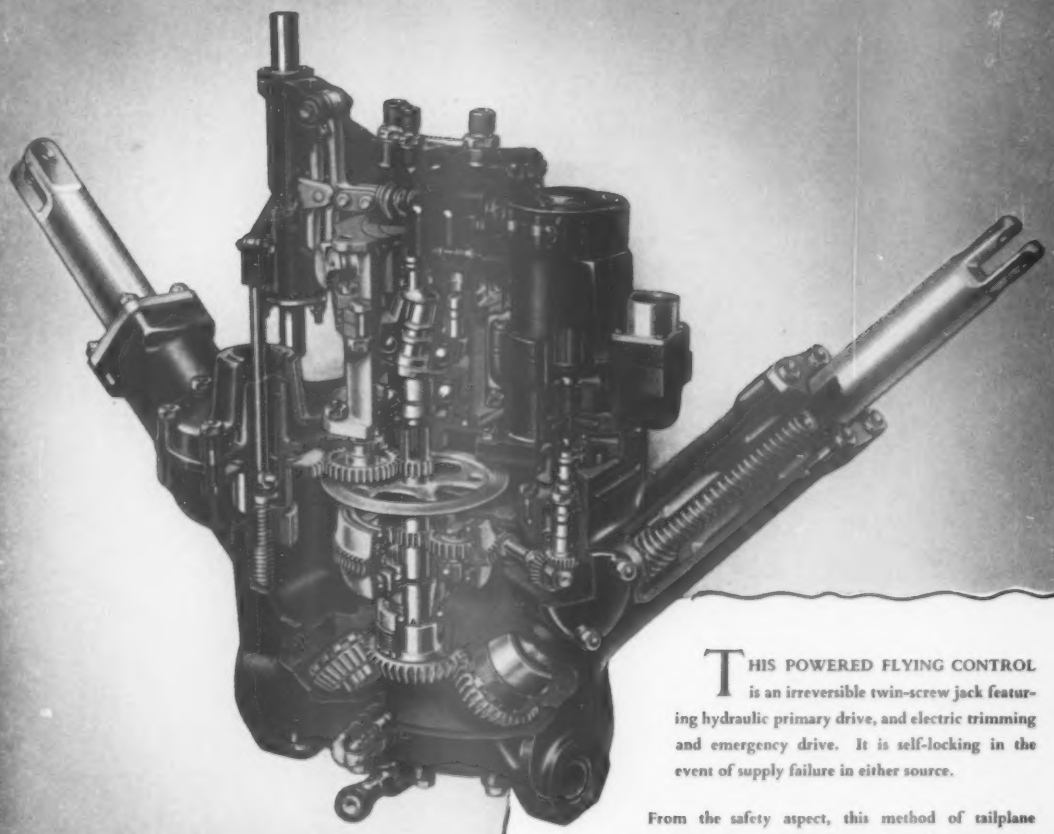

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